53 p

08
N64-17493 *
Code 1

AR53257

EXPERIMENTAL INVESTIGATIONS ON SOLID SPOILERS AND JET SPOILERS AT MACH NUMBERS OF 0.6 TO 2.8

TRANSLATION NO. 32

FEBRUARY 21, 1964

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

(NASA Contract NAS7-100)
(NASA CR-53257; ~~JPL Trans. 32~~ JPLAI-Trans. 32) OTS: $ 5.60ph, $ 1.79 mf

ASTRONAUTICS INFORMATION

Translation No. 32

EXPERIMENTAL INVESTIGATIONS ON SOLID SPOILERS AND JET SPOILERS AT MACH NUMBERS OF 0.6 TO 2.8

A. Heyser and F. Maurer 21 Feb. 1964 53p refs

Trans~~lated~~ into ENGLISH from Z~~eitschrift für~~ Flugwiss~~enschaften~~ (Brunswick, W. Germany), v. 10, no. 4, 5, 1962

1304823

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA ~~CALIFORNIA~~
February 21, 1964

Prepared Under Contract No. NAS 7-100
National Aeronautics & Space Administration

CONTENTS

FIGURES

FIGURES (Cont'd)

EXPERIMENTAL INVESTIGATIONS ON SOLID SPOILERS AND JET SPOILERS AT MACH NUMBERS OF 0.6 TO 2.8[1]

A. Heyser, F. Maurer

ABSTRACT

17443 A

Experimental investigations are reported regarding the effects of solid and jet spoilers on a flat plate in high-subsonic and supersonic tangential flow. The boundary layer of the plate is turbulent ahead of the separation at the spoiler. The height of the spoiler varies between 0.2 and 0.8 cm; the ratio of the stagnation pressure of the control jet and the static pressure in the test section varies between 3 and 60. The results of force and pressure distribution measurements are reported and discussed in relation to the flow pattern, and are compared with the measurements thus far available. The lift-drag ratio of the solid spoiler is compared with an analogic term of the jet spoiler. This term is shown to be in the order of magnitude of 2 in the supersonic range for the solid spoiler at the end of the plate, and may be considerably exceeded in the case of the jet spoiler. High-frequency schlieren photographs have been produced of the spoiler in motion, in order to discuss the response time.

Author

[1]Supplied by the Institute für Angewandte Gasdynamik der Deutschen Versuchsanstalt für Luft- und Raumfahrt (DVL) (Institute for Applied Gasdynamics of the German Research Center for Aeronautics and Space Flight). This investigation was made available through the German Defense Ministry. These tests were possible through a considerable contribution by Stanewski and Leucht, to whom much appreciation is extended. Measuring instruments made available by the German Institute of Scientific Research rendered an invaluable service.

I. INTRODUCTION

The purpose of spoilers arranged on wings or ailerons of flying missiles is a better control by influencing the lift. A solid spoiler is an impact-pressure plate installed almost perpendicularly on the surface and of little height, in general, as against the depth of the profile. This type of control is particularly advantageous for remote control of flying missiles because it provides small control forces, rapid response time, and the possibility of adaptation to control patterns by variation of the width of impulse.

Aerodynamic aspects of spoiler control consider (1) lift-decreasing spoiler effects at small speeds, with the spoiler arranged at best on top surface of the profile; and (2) lift-increasing spoiler effects at high speeds, in particular in the supersonic range, with the spoiler arranged at the bottom surface of the profile. The first kind (1) of spoiler effect was so named due to the fact that with increasing height of spoiler, the circulating flow undisturbed so far around the profile is getting spoiled and the lift is decreased at the same time. Spoiler effects of this kind, however, will not be dealt with by this treatise; the many investigations accomplished on that subject matter have been reported by several former publications of DVL (Ref. 1, 2, 3).

Experiences with high flight speeds have shown that the effect of a spoiler control (favorable for lower speeds) as from a "critical" Mach number is becoming considerably smaller and may lead to inefficiency or even reversal of the control effect (Ref. 4, 5). For this critical range, as well as for supersonic speeds, insufficient test material has been published; consequently, DVL has made several investigations during the past years on spoilers under high speed conditions.

Whereas at lower speeds it was always important to examine the profile and the spoiler on the whole, the transition to high speeds, and to supersonic speeds in particular, shows a concentration of the spoiler effect on a limited profile area near the spoiler, by which an elimination of the spoiler effect on the reverse side of the profile is experienced. Moreover, since the spoiler heights are practically small as compared with both depth of profile and its local radius of curvature, experimental as well as theoretical investigations would suggest that in the first instance the effect of the profile be disregarded and only the spoiler effects on flat plates in tangential flow be considered. For this purpose it is desirable to obtain measurements of two-dimensional values by means of the most favorable lateral conditions as well as, experimentally, by the use of lateral plates, of the degree of the influence of cross flows. In the case of jet spoilers, one utilizes, instead of solid spoiler plates, a kind of slotted nozzles with control jets exhausting perpendicularly to the main stream. Jet and solid spoilers are compared with regard to their control effect.

Measurements made by the Institute for Applied Gasdynamics of the DVL include both solid spoilers 0.2 to 0.8 cm high and jet spoilers with stagnation pressures of 3 to 60 ata and static pressures in the test section of about 1 ata.

These measurements were made at Aachen in the vertical free-stream test section of the overpressure and supersonic tunnel (Ref. 24) in the Mach number range of $M = 0.6$ to 2.8.

A part of the results regarding solid spoilers has been utilized from measurements made for the Bolkow-Entwicklungen (Developments Co.) at Ottobrunn.

II. INVESTIGATIONS ON SOLID SPOILERS

A. Test Methods

For measurements on solid spoilers, the following methods were applied:

1. *Measurement of the integral air forces by means of multi-component balance (Fig. 1a, 2).* The balance is installed in a flat enclosure, on the top surface of which the measuring plate is arranged. Several spoilers can be set either in the middle or at the end of the measuring plate, which is surrounded by a shielding plate that is solidly connected with the enclosure. Two small brass sliders with springs are used as gaskets between the two plates. It is practicable to arrange lateral plates on the baseplate in order to obtain an approximately two-dimensional flow condition. By means of the balance, it was possible to determine for the measuring plate the normal force, the tangential force, and the air attack point.

This measurement method is advantageous insofar as the air forces can be measured and spoilers of any form can be examined. There were mechanic difficulties, however, for the sealing of the sliders of the measuring plate and with regard to the proper adjustment of the measuring plate against the shielding plate, so that the accuracy of measurement was less satisfactory than with the methods explained below.

2. *Measurements of the pressure distribution.* A certain number of measuring boreholes were arranged afore and behind the spoiler and were connected to an electronic multi-manometer (Ref. 25). Normal force has been found by integration of the measured pressure distribution.

3. *Measurements of pressure distribution on spoilers in motion (Fig. 1b).* This method used four boreholes in the baseplate at differing distances from the on-flow edge. During the measurements and by means of a special device, the spoiler was guided across the plate, and the pressure flow at each of the boreholes was recorded continuously via quick-response pressure contacts. Moreover, current checkings of the continuous pressure flow were made by point measurement of pressure. For each of the four boreholes, measurements have been made at differing medium Reynolds reference numbers.

4. *Measurements of the tangential force of the spoiler by means of a stick-type balance (Fig. 1c).* This type of balance has been utilized to supplement the measurements on the baseplate by measurements of force to determine the tangential force. The spoiler has been connected with the shielded balance by two small clamps. The air forces acting on the part of this holding device protruding from the shielding have

been determined by special measurements, during the course of which the holding was shielded by a blind spoiler. The forces on the holding device were below 5% of the total forces measured.

B. Test Results

In the range of subsonic speeds, it is possible to obtain great spoiler effects by the arrangement of the spoiler on an appropriate spot of a selected wing profile, so that the extended spoiler causes a separation of flow and thereby a considerable alteration of the lift distribution. When approaching the speed of sound, on profiles in particular, there is a remarkable influence acting on the flow pattern by the intervention of local supersonic sections with final compression shocks. Since the investigations covered high flight speeds for which only very flat profiles are used, the tests disregarded any profile effect and concentrated on spoiler effects on flat baseplates.

1. Flow Pattern. Figures 3 and 4 show typical schlieren photographs, with relevant pressure distributions explaining the characteristic attitude of spoiler arrangements examined in the ranges of high subsonic and supersonic speeds.

In the case of high subsonic speeds, Fig. 3 shows the interrupting effect of the solid spoiler by the turbulent area starting at the upper edge of spoiler. Ahead of the spoiler is a developing area of compression, with increasing gradients leading to the separation of the boundary layer. The schlieren photograph shows clearly the separation area ahead of the spoiler, bordering at the upper spoiler edge. This area has a pressure of an approximately constant value. Above the spoiler can be seen an expansion area leading, in the case of high subsonic speeds ($M > 0.85$), to local supersonic speeds and a series of λ-shocks starting from the turbulent area. The area of negative pressure developing behind the spoiler is filled by the higher ambient pressure so that the flow pattern adapts to the latter. A substantial drag results from overpressure on the front side and negative pressure on the back side of the spoiler.

The flow pattern in the supersonic range shown in Fig. 4 differs essentially from the one that would be given for an impact-pressure plate resulting from the spoiler reflection at the baseplate. Theoretical considerations first assumed such a flow pattern (Ref. 6). Due to the boundary layer at the baseplate, however, there is a wedge-shaped separation area ahead of the spoiler similar to the one of a half-wedge in flow. The separation point of the boundary layer shows a series of compression waves merging into a slanting compression shock. Close examination of this point shows that the advancing overpressure area first causes an expansion of the boundary layer, and that the separation begins somewhat downstream. The pressure increase in the separation range does not occur suddenly at a constant value as in the case of a solid wedge, but, in consequence of the boundary layer on the plate and because of the flow conditions of the separation area, with a final gradient that leads for higher spoilers to an approximately constant pressure or a flat maximum of pressure. Ahead of the front area of the spoiler, however, there is an additional pressure increase which results from the impact pressure and the special flow conditions ahead of the spoiler surface (Fig. 5b). A compression shock showing a somewhat steeper curve forms before the downstream area at the upper spoiler edge. In the case of thicker spoilers, there are two separate expansion areas on the upper spoiler edge near its corners. The expansion on the back side of the spoiler causes the setting of flow and the formation of a "tail wave". The setting of the flow corresponds to approximately the static ambient pressure on the baseplate.

The flow pattern on the baseplate around a spoiler without lateral plates (height 0.6 cm, length 5.9 cm) at $M = 2.21$ has been photographed (Fig. 5a) with the aid of a solution of oil and black chalk. There is a remarkable lateral effect, and the upstream separation zone is slightly curved so that clear two-dimensional conditions are not prevailing. The separation areas before and behind the spoiler show strong setting stripes, indicating the existence of encountering turbulent zones (Fig. 5b). These turbulent zones developing in the upstream area are sliding beyond the sides of the spoiler. The setting of flow behind the spoiler can be seen by an accumulation of color particles within the downstream area, especially just behind the spoiler, caused by counter-rotating eddies in castor action.

Thorough investigations in the flow area before a step, i.e., in the area ahead of the spoiler, have been carried through by Bogdonoff and his staff (Ref. 8, 9, 10).

2. *Measurements of pressure distribution in the high-subsonic range.* In the high-subsonic range, measurements have been made for solid spoilers (height: 0.3 to 0.8 cm) with and without lateral plates, at Mach numbers of 0.6 up to 0.98 and with angles of attack of the baseplates of $\alpha = 0$ to 6. Reynolds numbers were between $Re = 1.4 \cdot 10^6$ and $4.4 \cdot 10^6$.

Figures 6a through 6d show the pressure flows measured ($\Delta p/q$) ahead and behind the spoilers (spoiler front edge at $x = 0$). The effects of both Mach number and height of spoiler can be considered by comparing the pressure areas. Tests without lateral plates (Fig. 6a, b) showed about the same values for the effects of high and low pressure, so that with a solid spoiler with the full effects of the high- and low-pressure areas the normal force becomes $N \approx 0$, though there is a momentum prevailing. The test methods with lateral plates (Fig. 6c, d), however, showed larger low-pressure areas, so that the resulting normal force is negative.

A comparison of measurements made with and without lateral plates (Fig. 6c) shows still a remarkable influence of cross streams for a spoiler width of 10 cm if no lateral plates are used. The utilization of lateral plates increases the peak pressure as well as the extension of both supersonic and subsonic areas. Yet, it should be noted that lateral plates, too, do not warrant clear two-dimensional flow conditions due to interferences from on-flow edge and because of the partially separated boundary layers on the plates.

The pertinent measurements made with variable angle of attack of the baseplate (Fig. 6d) showed, within the range examined, only a minor influence of the angle of attack on the spoiler effect.

The schlieren photograph (Fig. 7) shows more details of the flow pattern.

3. *Measurements of pressure distribution in the supersonic range.* Measurements were carried through at $M = 1.57$, 1.83, 2.21, and 2.80 for spoilers with and without lateral plates. Reynolds numbers, on average, referred to starting length x_s, were $Re = 5.2 \cdot 10^6$ to $24 \cdot 10^6$.

Measurements of pressure distribution (Fig. 8a through d) as well as schlieren photographs (Fig. 9, 10) show a clear decrease of the area of influence due to the spoiler caused by increasing Mach number and decreasing height of spoiler.

This trend, however, at increasing Mach numbers has been observed for values up to $M = 2.21$. The distance of the point of separation to the front edge of spoiler increases again at $M = 2.80$ (Fig. 8c and d). For all spoiler heights and at constant Mach number, the first peak pressure is approximately the same. However, the previously mentioned pressure peak, directly ahead of the spoiler, is existent with higher spoilers only. For heights below 0.4 cm, i.e., when the spoiler progressively merges into the boundary layer, this pressure peak as well as the first one with higher spoilers is not obtained.

The low-pressure area behind the spoiler compensates a great portion of the high-pressure effect ahead of the spoiler if the two portions of the normal force acting against each other become fully effective.

The measurements of pressure distribution show, additionally, that, in the case of a spoiler mounted on a flat plate, at increasing Mach numbers the high-pressure effect ahead of the spoiler gains more and more as against the low pressure behind the spoiler. This is largely true of flat high-speed profiles, so that the most favorable position of a solid spoiler for high-flight speed is the end of the baseplate. Consequently, in the following explanations all resulting coefficients refer to such an end spoiler. For other spoiler positions, these coefficients can be derived by comparison of the respective area from the measurements of distribution of pressure.

Figures 8a through 8d show an increase of the high-pressure area ahead of the spoiler as against the low-pressure area. A spoiler with both areas fully effective results in an increasing normal force in the supersonic range at increasing Mach numbers. This trend is evident by the fact that the impact-pressure increases with rising Mach numbers, but that the low-pressure behind the spoilers in the supersonic range approaches a limiting value.

Figure 11 shows a comparison of measurements with and without lateral plates. At low supersonic Mach numbers this influence is particularly evident by a deviation of the point of separation. At $M = 1.83$ this influence of the lateral plates is noticeably less important (Fig. 12).

Two-dimensional flow conditions can be obtained, approximately, by the use of lateral plates and if the ratio of the sides is not too small. The lateral plates caused minor derangements due to (1) a slight compression shock from their on-flow edge (a matter that could not be avoided from the design side) and (2) the increasing boundary layers on the plates. A certain risk of blocking could be avoided by a minor angle of attack of the lateral plates.

4. *Coefficients.* Figure 12 shows the coefficient of the normal force for the end spoiler (Δc_n), as well as other results known from the pertinent literature. The Δc_n development as a function of the Mach number is approximately the same as for a flat profile and in the case of a constant angle of attack. The increase of the Δc_n -value in the subsonic range adapts in principle to the rule of Prandtl and Glauert, as it has been stated by Ernst (Ref. 4). Figure 12 shows equally some calculated points resulting from the measuring point at the lowest applied Mach number. The Δc_n -curve in the supersonic range runs approximately parallel to the values calculated by Seibold (Ref. 6) for an impact-pressure plate, but essentially lower since the flow pattern does not correspond to the condition of the calculation and due to the fact that the pressure increase behind normal shock is not reached. The differences between Δc_n -values for spoiler heights of 0.2 to 0.8 cm are not very significant in the supersonic range. The greater values correspond to the smaller spoiler heights. Influence by the lateral plates is important in the subsonic and the lower supersonic ranges.

A good correspondence has been obtained between the measurements of pressure distribution and of the balance.

Measurements on profiles carried out by Goethert (Ref. 5) and Poisson-Quinton and Jousserandot (Ref. 11) show, as already mentioned, remarkably higher lift coefficients than the measurements on a flat plate. Those values decrease considerably, however, above the critical Mach number. The latter kind of measurement does not refer to end spoilers ($x_s/t = 0.953$), so that the Δc_n values in supersonic range have to be below the values quoted here.

Figure 12 also shows the measurements made known by Naumann on occasion of the 1955 WGL Meetings (Ref. 7). Although these measurements were made by means of a very small wind tunnel at the Technical University (TH) of Aachen, values quoted for a height of 0.3 cm in the supersonic range correspond perfectly to those of recent measurements.

Measurements of coefficients of normal force, done by means of a special balance at different angles of attack ($\alpha = -3$ to $+3$ deg) (Fig. 13a), show in the supersonic range a constant decrease of normal forces with negative angles of attack, i.e., when the spoiler disappears for the air flow behind the on-flow edge. The relevant coefficients of tangential force are shown in Fig. 13b.

A trend similar to that given by the lift coefficients was obtained in the supersonic range by measurements of the tangential force by means of the rod-type balance (Fig. 14). The two measuring points as received from the spoiler balance are less precise for the reasons explained above. When considering the measured Δc_T -values in the supersonic range and the corresponding coefficients for an impact-pressure plate ($c_T \approx 1.7$), there is a comparable decrease that corresponds to the difference between the measured coefficients of normal force and the values calculated by Seibold (Fig. 12).

It should be noted that a calculation of the tangential force – which results from the pressures directly ahead and behind the spoiler – leads to values that differ only slightly from the direct measurements of force.

When the ratio $\Delta c_n/c_T$ (Fig. 15) is formed, an approximate ratio of 2 can be supposed for the solid spoiler in the supersonic range ($M > 1.8$). Therefore, the drag portion of the spoiler is remarkably great. It should be noted that the spoiler drag, e.g., in the case of a listed empennage, is likely to support the effect of the spoiler control by the momentum given.

All measurements were made with a turbulent boundary layer. A variation of the Reynolds number at the ratio of approximately 1:2 resulted from the measurements of the pressure distribution with a mobile spoiler; however, there was no influence of the Reynolds number to observe.

III. INVESTIGATIONS ON JET SPOILERS

The jet spoiler could be of particular interest when used on space vehicles traveling at great altitudes and very low atmospheric densities, and for which only a reaction control is practicable. When a jet control is to be used beyond the atmosphere, it is at once important to know which control effect will be obtained within the atmosphere, since with an appropriate spoiler arrangement the effect of repulsion can be essentially increased by interference of the control jet with the air flow. Whereas under vacuum conditions the control effect can be easily calculated, atmospheric conditions would be quite complex and could be determined only by experiments for high-flight speeds, due to influences resulting from interference and boundary layer.

Moreover, the use of a jet spoiler also seems to be advantageous for air missiles traveling within the atmosphere only. Whereas the arrangement of a solid spoiler with its control element on the rear edge of a slender profile for supersonic speeds presents serious mechanical problems, it is relatively easy to design a narrow control slot. Operating the jet spoiler is practicable by means of a magnetic valve arranged evenly at a certain distance from the control slot.

The control air required for the jet spoiler can be taken from the combustion chamber for a jet-propelled design, or from the atmosphere by means of a special intake. In some cases it may be necessary to carry along specific high-compression or liquefied gases.

A. Testing Arrangements

Figure 16 shows the model of a jet spoiler in the free-jet test section of the supersonic-speed tunnel at Aachen (Technical University). The flat plate with sharpened front edge can take slides with various forms of control slots. The plate has 40 borings, before and behind the slot, in staggered arrangement. Pressure measurement was made by a measurement-point change-over switch (Scannivalve) with a built-in pressure device (Statham) by means of which all measurement spots could be scanned within 3 sec and recorded by a loop-oscillograph (Visicorder).

Measurement conditions were as follows:

Mach number $M = 0.6$ up to 2.8

Reynolds reference number $Re = 1.4 \cdot 10^6$ up to $12 \cdot 10^6$

Ratio of pressure $p_{0_i}/p_\infty = 3$ to 60

Width of control slot $s = 0.1$ or 0.033 cm at sonic-speed exhaustion of control air

Length of slot $b = 4.8$ cm

B. Test Results

1. Flow pattern. Figures 17, 18, and 19 represent typical schlieren photographs of the exhaustion of a lateral control jet without external stream, and a baseplate in subsonic and supersonic flow.

The control jet exhausting from a slot with a convergent exit (Fig. 17) shows the typical image of a jet in high pressure exhaustion, with the characteristic formation of "barrels". With higher control pressures, the jet limits would quickly dissolve in turbulent zones; sound waves from there can be seen on schlieren phötographs.

With subsonic on-flow (Fig. 18), there is not the sharp rupture of the main stream behind the point of interference, as is the case with solid spoilers. The flow would be deviated by the exhausting control jet, according to the selected ratio of pressure p_{0_i}/p_∞ With high-subsonic speeds, there would be local supersonic areas with final impact-pressure shocks likewise in the main stream.

The flow pattern of a jet spoiler in supersonic speed (Fig. 19) is very similar to that of a solid spoiler. The control jet also under high control pressure is quickly deviated in flow direction. The formation of the wedge-shaped flow separation ahead of the control jet, with the bow shock, is, in comparison to the height of the spoiler, dependent in this case on the control pressure. A "separation shock" beginning on the area of discontinuity and joining the bow shock sets before the blunt barrier imposed by the control jet. The area of overlapping with the main stream shows strong alterations of density. The characteristic lines should be understood, partly, as areas of discontinuity and not as impact-pressure shocks. At the upstream-situated area of discontinuity of the exhausting control jet, there is an impact-pressure shock with strong curvature setting about perpendicularly to the exhausting direction of the control jet and contributing to the deviation of the latter. As can be seen from the distribution pattern of pressure, considerable low pressure exists in the separated area behind the control jet, though it sets quickly near the plate. Here again the castor action is characterized by a tail wave directing the total stream parallel to the plate.

In order to further explain the flow pattern, photographs have been made (with the aid of an oil and dark chalk mixture) of the baseplate and specially designed large lateral plates (Fig. 20, 21). The mixture – mineral oil and titanic oxide – has been applied prior to the test to the baseplate and the lateral plates; during the test it moves with the flow in the boundary layer. A part of the liquid evaporates and is blown away, leaving a white deposit indicating the flow lines near the wall. Where a great flow speed is prevailing, the deposit is almost entirely blown away; however, on areas of discontinuity, turbulent zones, or separations of the boundary layer, there are heavier deposits.

Figure 20 shows, somewhat unsharply, the flow on the baseplate. Clearly visible is the form of the separation area and its modification by the lateral plates. The photograph of a large lateral plate (Fig. 21) should be compared with the schlieren photographs of Fig. 22 and 23. It should be noted, however, that the photograph of Fig. 21 was made in an oblique direction to the lateral plate.

Figure 21 shows clearly the bow shock, the area of separation, and the tail wave; it shows equally the direction of the flow lines and, in particular, the direct zone of influence of the control jet. With high control pressures, the latter would be directed, rather soon, in the direction of the main stream.

2. *Pressure distribution.* Figures 24 and 25 show the measured pressure distributions for several Mach numbers and control pressures. According to the spoiler height in the case of a solid spoiler, the point of separation under consideration is shifting upstream the more the control pressure increases. As opposed to the results with solid spoilers, it is remarkable that with jet spoilers the peak-pressure areas situated directly ahead of the control slot are considerably greater. The physical explanation for this fact can be seen from the schlieren photographs of Fig. 19, 22, and 23. With greater ratios of pressure p_{0_i}/p_∞, the expanding control jet presses the heavy impact-pressure shock ahead of the control jet considerably more upstream than is the case for the respective shock with a solid spoiler. At $M = 1.83$, there would be values of $p_{max} = 0.55\,q$ for the jet spoiler and of $p_{max} = 0.449$ for the solid spoiler. The development of pressure increase, the first pressure peak in the wedge-shaped separation area, as well as the pressure development in the castor action are very similar with both types of spoiler.

For the control effect of a jet spoiler at the end of a surface, it is possible to compare it with the solid end spoiler by means of the surfaces of the high-pressure areas. It should be remembered that the high-pressure effect with a jet spoiler ahead of the control slot is supported by the repulsion effect. At $M = 1.83$, the control effect obtained in the case of a jet spoiler with control slot width of $s = 0.1$ cm and a pressure ratio p_{0_i}/p_∞ of about 20, for instance, would be the same as for a solid spoiler of 8-mm height.

3. *Definition of the coefficients.* The following presentations have been selected to specify reasonable coefficients for the control effect of the jet spoiler and to allow a comparison with the solid spoiler:

$$\frac{N_i}{N_v} = f_1 \quad M\left(\frac{p_{0_i}}{p_\infty}\right), \tag{1}$$

$$\frac{N_i + R_k}{S_{\max}} = f_2 \quad M\left(\frac{p_{0_i}}{p_\infty}\right) \tag{2}$$

N_i represents the normal force given by the interference with the external flow if the integration of the pressure distribution is carried out in the forefield of the control jet only. The reference value

$$N_v = 2\left(\frac{2}{\chi - 1}\right)^{1/\chi + 1} p_{0_i}\, \mu\, s \tag{3}$$

is the normal force that would be given by the repulsion effect of the control jet exhausting at the speed of sound under vacuum conditions. The coefficient μ for the jet contraction in the critical cross section of the control slot has been determined experimentally by measurements of repulsion and of pilot pressure distribution in the control slot; its values were between 0.90 and 0.99, rising with increasing pressure ratio p_{0_i}/p_∞. The values determined by calculation N_v, R_k, and $S_{\max}$ have been corrected by the experimental value for μ.

When the control jet exhausts from a convergent nozzle at sonic velocity against pressure p_∞ there will be a repulsion effect of

$$R_k = \left[2\left(\frac{2}{\chi - 1}\right)^{1/\chi + 1} p_{0_i}\, \mu - p_\infty\right] s. \tag{4}$$

In order to determine a value for the jet spoiler which will correspond to the ratio $\Delta c_n/\Delta c_t$ for the solid spoiler, the control effect of the former has been given a relation to the force that could be obtained for the control jet as the maximum thrust

$$S_{max} = p_{0_i} \, \mu \, s \, \chi \sqrt{\frac{2}{\chi - 1} \left(\frac{2}{\chi + 1}\right)^{\chi + 1/\chi - 1}} \sqrt{1 - \left(\frac{p_\infty}{p_{0_i}}\right)^{\chi - 1/\chi}} \qquad (5)$$

by expansion at equal-pressure exhaustion in a lateral nozzle.

4. *Discussion of the results of measurement.* It can be seen from Fig. 26a and 26b that the control effect of a jet spoiler, as opposed to the repulsion effect, decreases with rising control-pressure ratio due to interference. It would be the same with constant control pressure at an increasing flight altitude. With control pressures $p_{0_i}/p_\infty < 4$, there were equally measurements of decreasing values for N_i/N_v. The maximum values experimentally found were with $N_i/N_v \approx 10$ for a width of the control slot of $s = 0.1$ cm, and a ratio of control pressure of $p_{0_i}/p_\infty \approx 3$, i.e., the control effect obtained by interference with the main stream is, under these conditions, ten times as great as the repulsion effect of the control jet under vacuum conditions. However, the control force attainable in this range is rather small, so that its practical importance is questionable. With higher control pressures ($p_{0_i}/p_\infty > 10$), the measured values for N_i/N_v are between 1.9 and 0.75 with a minimum in the supersonic range for $M = 1.83$ at $p_{0_i}/p_\infty > 16$. With higher Mach numbers the control effect will be increasing.

The influence of the lateral plates can be seen by comparing Fig. 26a and b.

A series of treatises by American authors have been issued recently about jet spoilers (Ref. 13 to 22). The results found by Romeo and Sterrett (Ref. 22) for $M = 6$ with comparable width of slot are above the measured values found by the DVL in the range of higher control pressures (Fig. 26a); this is due to the high Mach number and the greater length of the control slot, in accordance with the above mentioned trend. With lower control pressures, however, the increase of the interference effect is entirely lacking. A decreasing trend of peaks for N_i/N_v with low control pressures and at rising Mach number has been found equally by the present tests. However, for narrow slots ($s = 0.00254$ cm) and with ratios of control pressure of $p_{0_i}/p_\infty = 200$ to 400, values of N_i/N_v up to 9.5 have been found by Romeo and Sterrett. With these measurements an essential influence by the condition of the boundary layer has equally been found.

The results of a simplified theory of Vinson, Amick, and Leipmann (Ref. 20) are likewise entered in Fig. 26a. These theoretical values are considerably below present experimental results; the trend of the curves, however, correspond to the results of the measurements. Greater differences are due, in particular to the neglecting of the strong over expansion of the control jet.

The total control effect ($N_i + R_k$) of the tested jet spoilers in relation to the maximum thrust (S_{max}) obtainable by means of the control air can be seen in Fig. 27.

An essential influence on the control effect obtainable by the interference of control jet and main stream is given by the width of the control slot (Fig. 28). Tests carried out with a width of control slot $s = 0.033$ cm supplied for the high control pressures up to 80% greater values for N_i/N_v than for the width of control slot $s = 0.1$ cm. It should be noted, however, that the quoted reduction of the width of slot means an increase of the ratio of the sides, and that the influence of the lateral flow decreases on the ends of the control slot with rising ratio of the sides.

IV. COMPARISON OF SOLID SPOILERS WITH JET SPOILERS

The comparison of the effect of solid and jet spoilers can be made from the data supplied by Fig. 29. Indicated there is the obtained normal force in relation to the additional draft or to the optimum of thrust effect for the two control methods. Supposing an approximate value $\Delta c_n/\Delta c_t = 2.2$ for the solid spoiler without lateral plates, the jet spoiler for all values $(N_i + R_k)/S_{max} > 2.2$ is superior to the solid spoiler in the effect and in a wide range.

It should be noted that the test arrangements applied thus far have been freely selected and do not represent the most favorable conditions. Further investigations already prepared will include some modifications, such as changes in width of slot, supersonic expansion in the control slot, inclination of the control jet against the direction of flow, end position of a control slot, and arrangement of several control slots one behind the other. Moreover, tests will comprise higher Mach numbers and smaller density of the main stream, thereby allowing the use of a model with greater side ratio.

V. UNSTATIONARY PROCESSES WHEN THE SPOILER IS EXTENDED IN SUPERSONIC RANGE WITH SUPERSONIC SPEEDS

It is to be expected that the locally limited stream area will develop with sonic or supersonic speed when the spoiler is suddenly extended. However, since the spoiler effect for a great deal is determined by processes in the boundary layer, it is questionable whether by this fact essential delay in response time would be conditioned. Therefore, a model (Fig. 30) has been designed on which the spoiler is extended in about 5 msec with the aid of a cam disc. This process has been taken by a high-frequency camera (Fastax) at a speed of approximately 5000 pictures/sec and an exposure time of 0.02 msec/picture (Fig. 31). The evaluation of these pictures indicates that the instantaneous photographs of the flow pattern show no differences to single pictures made for stationary conditions for the respective spoiler heights, i.e., both setting and form of shock are given by the given height of the spoiler at the instant of its extension. Shorter extension times than with these tests would hardly be obtainable in practical application.

Pictures made by Holder and Schultz (Ref. 23), on a protruding edge, in a shock-wave tunnel revealed times of composition for the flow pattern to be approximately 0.5 msec.

Some pictures of this film show that with changing flow pattern there are relatively sharp limits. In Fig. 32, a series of pictures show that with a retracting spoiler there are two impact-pressure shocks that disappear within 0.2 msec. The film shows equally that the flow pattern influenced by the spoiler comprises some local fluctuations, but that no pulsations were caused.

The same series of high-frequency pictures have been made for the jet spoiler. For the given arrangement, connecting the magnetic valve for the control jet with the control slot, a composition time for the flow pattern of approximately 10 msec has been obtained. By a more favorable wiring, this time could be shortened even more.

NOMENCLATURE

b	(cm)	length of spoiler or control slot
F	(cm^2)	surface of spoiler
h	(cm)	height of spoiler
s	(cm)	width of control slot
t	(cm)	depth of baseplate
x	(cm)	coordinate in longitudinal direction
x_s	(cm)	distance of the spoilers from the beginning of the plate
N	(kp/cm)	effect of force normally to baseplate/cm of spoiler length
N_i	(kp/cm)	normal force/cm of slot length due to interference of main stream and control jet
N_v	(kp/cm)	normal force due to repulsion of control jet/cm of slot length in a vacuum
R_k	(kp/cm)	effect of repulsion of the control jet/cm length of slot at exit of sound from a convergent control slot against p_∞
S_{max}	(kp/cm)	maximum thrust/cm slot length on expansion of the control jet on equal-pressure exit
T	(kp/cm)	effect of force tangentially to the baseplate/cm of spoiler length
p	(kp/cm^2)	local pressure on baseplate
p_∞	(kp/cm^2)	static pressure of the steady flow
p_{0_i}	(kp/cm^2)	stagnation pressure for control jet
$\Delta \rho$	(kp/cm^2)	$= p - p_\infty$
q	(kp/cm^2)	impact pressure $[= p_\infty (x/2) M^2]$
α	(°)	angle of attack
Δc_n	(1)	coefficient of normal force for spoiler effect in final position ($= N/hq$)
Δc_t	(1)	coefficient of tangential force ($= t/hq$)
Re	(1)	Reynolds code referred to x_s
M	(1)	Mach number
μ	(1)	coefficient for control slot
χ	(1)	ratio of the specific heats

REFERENCES

1. Kramer, M., Zobel, Th., Esche, G. C., *Lateral Controls on Spoilers of the DVL*, Center of Scientific Records, Berlin-Adlershof, 1941.

2. Bock, H., Ernst, G., Kramer, M., *Results of "Fritz X" Tests Made by the DVL at the Test Laboratories "South" at Foggia* (March 15 to April 10, 1942), DVL (Institute for Applied Gasdynamics of the German Research Center for Aeronautics and Space Flight) Report, ZLB-1/42, 1942.

3. Ernst, G., Kramer, M., *Development of Spoiler Controls for Remote Control of Flying Missiles*, NACA-TM 1210, National Advisory Committee for Aeronautics, Washington, D.C., 1949.

4. Ernst, G., *Control of Flying Missiles by Means of Spoilers*, unpublished report.

5. Goethert, B., *Effects of Spoilers in High-Subsonic Speeds*, Report 156 der Lilienthal-Gesellschaft für Luftfahrtforschung (O. Lilienthal Corporation for Aviation Research), 1942.

6. Seibold W., *Theoretical Evaluation of Spoiler Effects in the Supersonic Range*, Annual Report 1955 of WGL, pp. 192 – 202.

7. Naumann, A., *Comments on "Theoretical Evaluation of Spoiler Effects in the Supersonic Range"*, Annual Report 1955 of WGL, pp. 203 – 204.

8. Bogdonoff, S. M., Solarski, A. H., *A Preliminary Investigation of a Shock Wave Turbulent Boundary-Layer Interaction*, Aero-Engineering Report 184, Princeton University, Princeton, N. J., 1951.

9. Kepler, C. E., Bogdonoff, S. M., *Interaction of a Turbulent Boundary Layer With a Step at* $M = 3$, Aero-Engineering Report 238, Princeton University, Princeton, N. J., 1953.

10. Vas, E. I., Bogdonoff, S. M., *Interaction of a Turbulent Boundary Layer With a Step at* $M = 3.85$, AFOSR Report 295, TN 55-200, Air Force Office of Scientific Research, Washington, D. C., 1955.

11. Poisson-Quinton, Ph., Jousserandot, P., "Influence du Soufflage au Voisinage du Bord de Fuite sur les Caractéristiques Aérodynamiques d'une aile aux Grandes Vitesses" (Influence of Blowing Near the Escape Border or Aerodynamic Characteristics of a Wing at High Speed), *La Recherche Aéronautique*, no. 56, pp. 21 – 32, 1957.

REFERENCES (Cont'd)

12. Crocco, L., Probstein, R., *The Peak Pressure Rise Across an Oblique Shock Emerging From a Turbulent Boundary-Layer Over a Plane Surface,* Aero-Engineering Report 254, Princeton University, Princeton, N. J., 1954.

13. Mueller, J. N., *Investigation of Spoilers at a Mach Number of 1.93 to Determine the Effects of Height and Chordwise Location on the Section Aerodynamic Characteristics of a Two-Dimensional Wing,* NACA TN 4180, National Advisory Committee for Aeronautics, Washington, D. C., 1958.

14. Landrum, E. J., Czarnecki, K. R., *Pressure Distributions and Aerodynamic Characteristics of Several Spoiler Controls on a 40° Sweptback Wing at a Mach Number of 1.61,* NASA TN D-236, National Aeronautics and Space Administration, Washington, D. C., 1960.

15. Schult, E. D., *Free-Flight Investigation at Mach Numbers Between 0.5 and 1.7 of the Zero-Lift Rolling Effectiveness and Drag of Various Surface Spoilers and Jet Controls on an 80° Delta-Wing Missile,* NASA TN D-205, National Aeronautics and Space Administration, Washington, D. C., 1960.

16. Sterrett, J. R., Emery, J. C., *Extension of Boundary-Layer-Separation Criteria to a Mach Number of 6.5 by Utilizing Flat Plates With Forward-Facing Steps,* NASA TN D-618, National Aeronautics and Space Administration, Washington, D. C., 1960.

17. Morokovin, M. V., Pierce, C. A., Craven, C. E., *Interaction of a Side Jet With a Supersonic Main Stream,* Engineering Research Bulletin No. 35, University of Michigan, Ann Arbor, 1952.

18. Lowry, J. G., *Recent Control Studies,* NACA RM L 55 L 22a, National Advisory Committee for Aeronautics, Washington, D. C., 1956.

19. Ferrari, C., *Interference Between a Jet Issuing Laterally From a Body and the Eveloping Supersonic Stream,* Bumblebee Report No. 286, Johns Hopkins University, Baltimore, Md., 1959.

20. Vinson, P. W., Amick, J. L., Liepmann, H. P., *Interaction Effects Produced by Jet Exhausting Laterally Near Base of Ogive-Cylinder Model in Supersonic Main Stream,* NASA Memo 12-5-58 W, National Aeronautics and Space Administration, Washington, D. C., 1959.

REFERENCES (Cont'd)

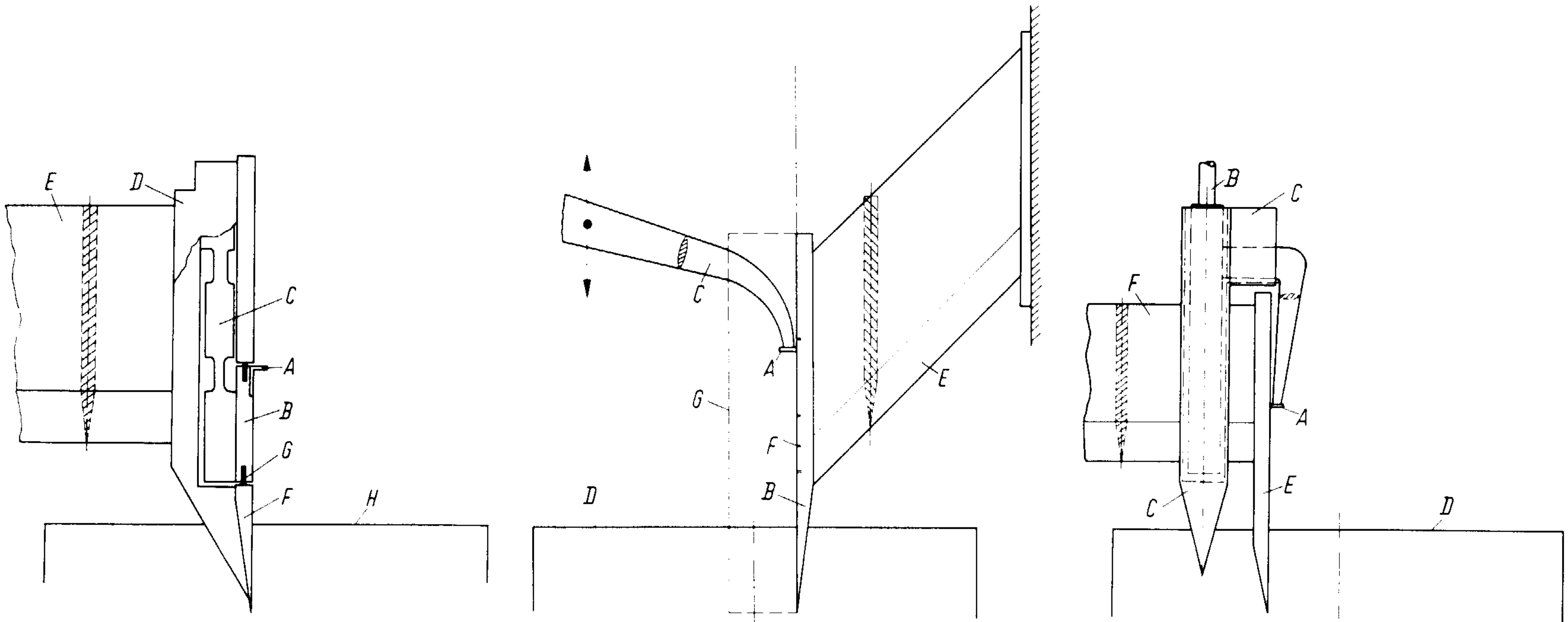
21. Janos, J. J., *Loads Induced on a Flat-Plate Wing by an Air Jet Exhausting Perpendicularly Through the Wing and Normal to a Free Stream Flow of Mach Number 2.0,* NASA TN D-649, National Aeronautics and Space Administration, Washington, D. C., 1961.

22. Romeo, D. J., Sterrett, J. R., *Aerodynamic Interaction Effects Ahead of a Sonic Jet Exhausting Perpendicularly From a Flat Plate Into a Mach Number 6 Free Stream,* NASA TN D-743, National Aeronautics and Space Administration, Washington, D. C., 1961.

23. Holder, D. W., Schultz, D. L., "On the Use of Shock Tunnels for Research on Hypersonic Flow". To be published in *Proceedings of the Second International Congress in the Aeronautical Sciences,* Zurich, 1960.

24. Naumann, A., Heyser, A., Trommsdorff, W., *The Over-Pressure Wind Tunnel at Aachen,* DVL (Institute for Applied Gasdynamics of the German Research Center for Aeronautics and Space Flight) Report No. 41, Annual 1957 of WGL, pp. 33–45.

25. Heyser, A., *An Electronic Multi-Manometer With Quick Response,* Annual 1957 of WGL, pp. 45–52.



(a) Spoiler arrangement for measurement of force by means of a built-in balance with extension strip

A = solid spoiler (heights: 0.4, 0.6, 0.8 cm; length: 5 cm)
B = measuring plate (length: 5 cm, depth: 6 cm)
C = built-in balance with tri-component measuring strip
D = enclosure of balance
E = holding sword
F = frame plate
G = gasket slide
H = exit valve of free jet

(b) Spoiler arrangement for continuous recording of pressure distribution

A = solid spoiler (heights: 0.2, 0.4, 0.6, 0.8 cm; length: 10 cm)
B = flat plate with four boreholes for measurement of pressure
C = holding arms for spoiler
D = valve exit of free jet (diam: 22 cm)
E = holding sword
F = boreholes for measurement of pressure
G = lateral plates (optional)

(c) Spoiler arrangement for measurement of the tangential force

A = solid spoiler (height: 0.6 cm, length: 6 cm
B = built-in balance
C = shielding of balance
D = valve exit of free jet (diam: 22 cm)
E = flat plate (in tangential flow)
F = holding device for plate and shield

Fig. 1. Test methods

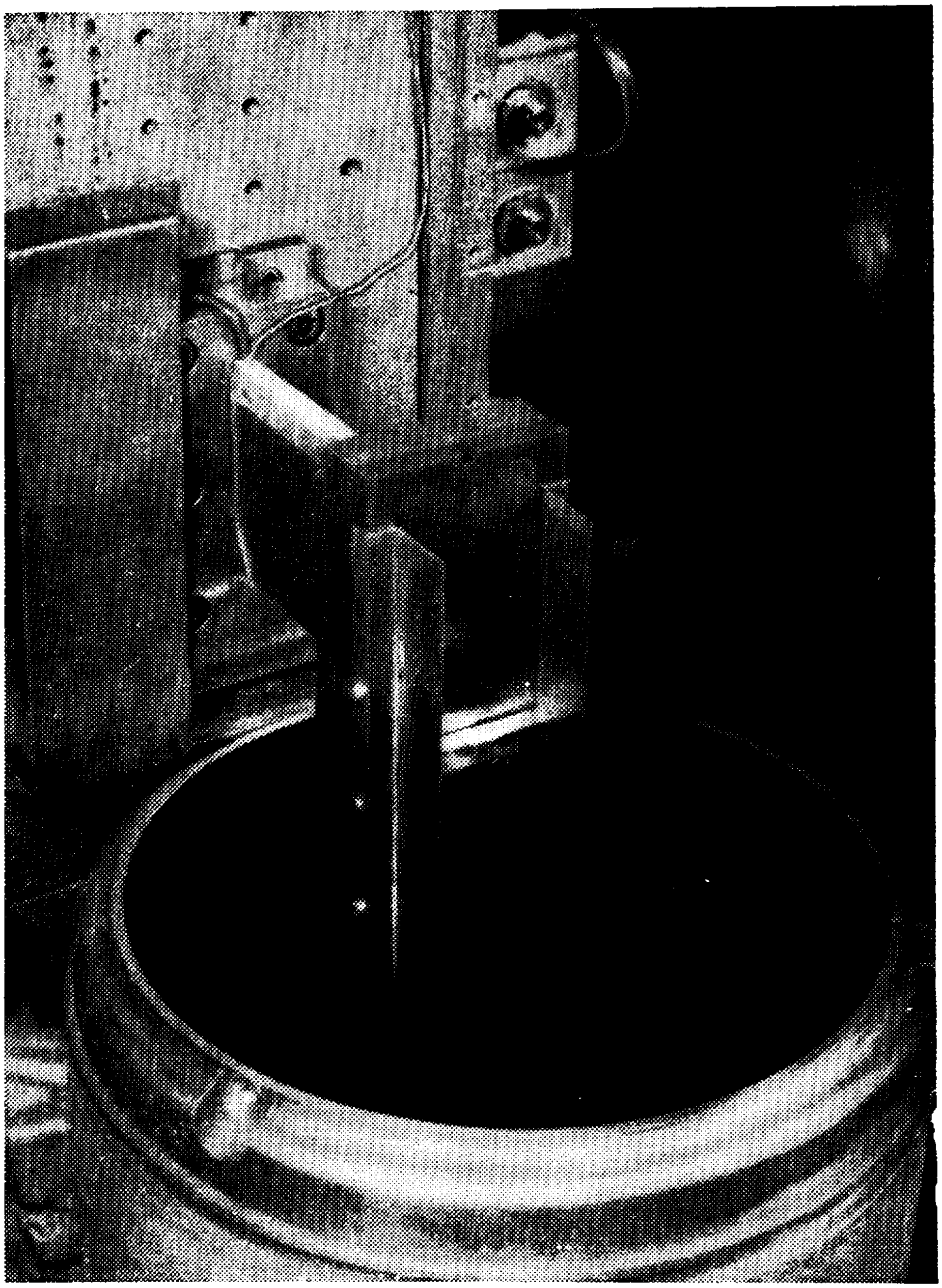


Fig. 2. Spoiler arrangement with mounted lateral plates in test section for measurement of force by means of a built-in balance with extension strip

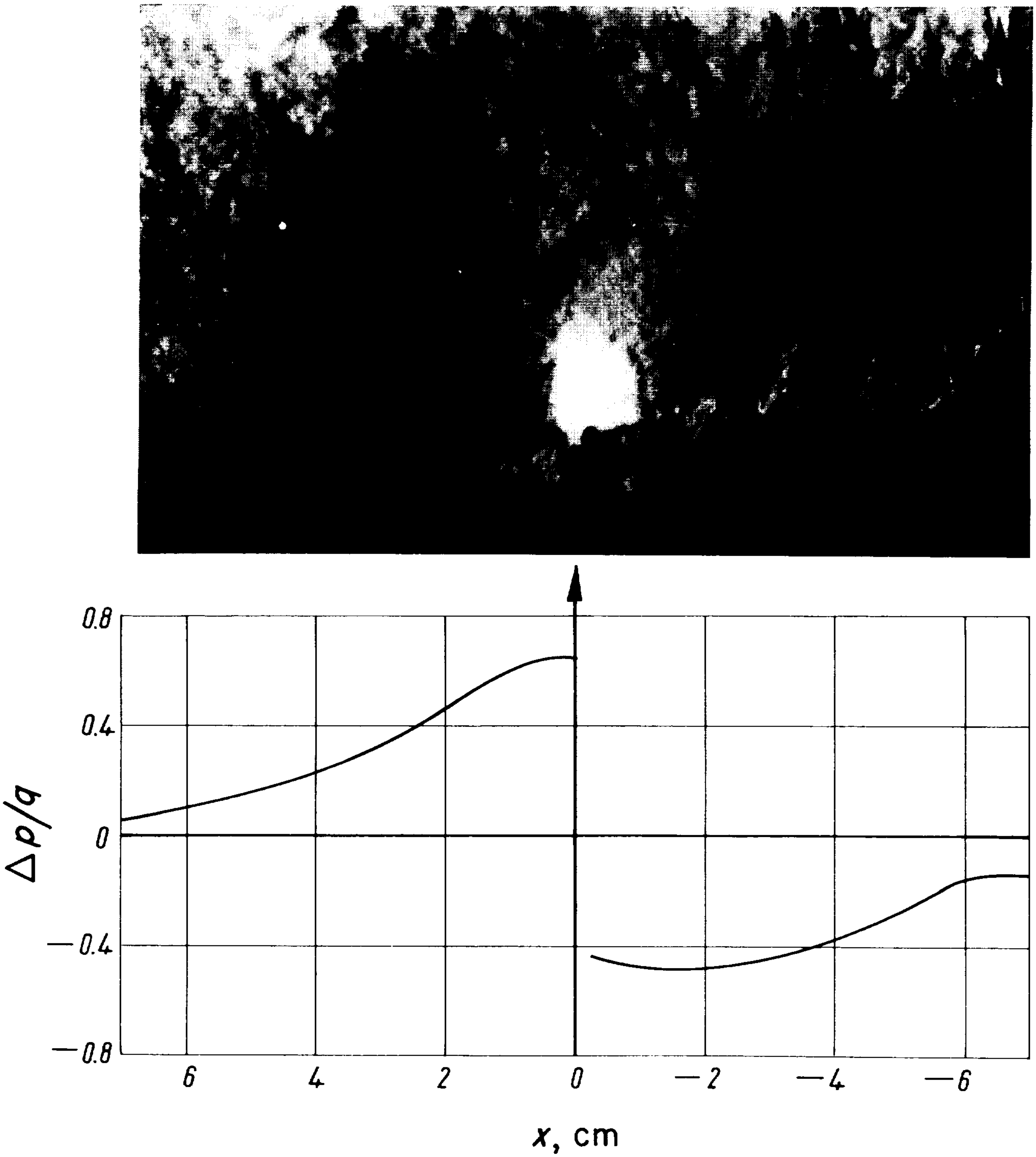


Fig. 3. Flow pattern of solid spoilers in the high subsonic range and the relevant pressure distribution; $M = 0.87$, height: 0.6 cm

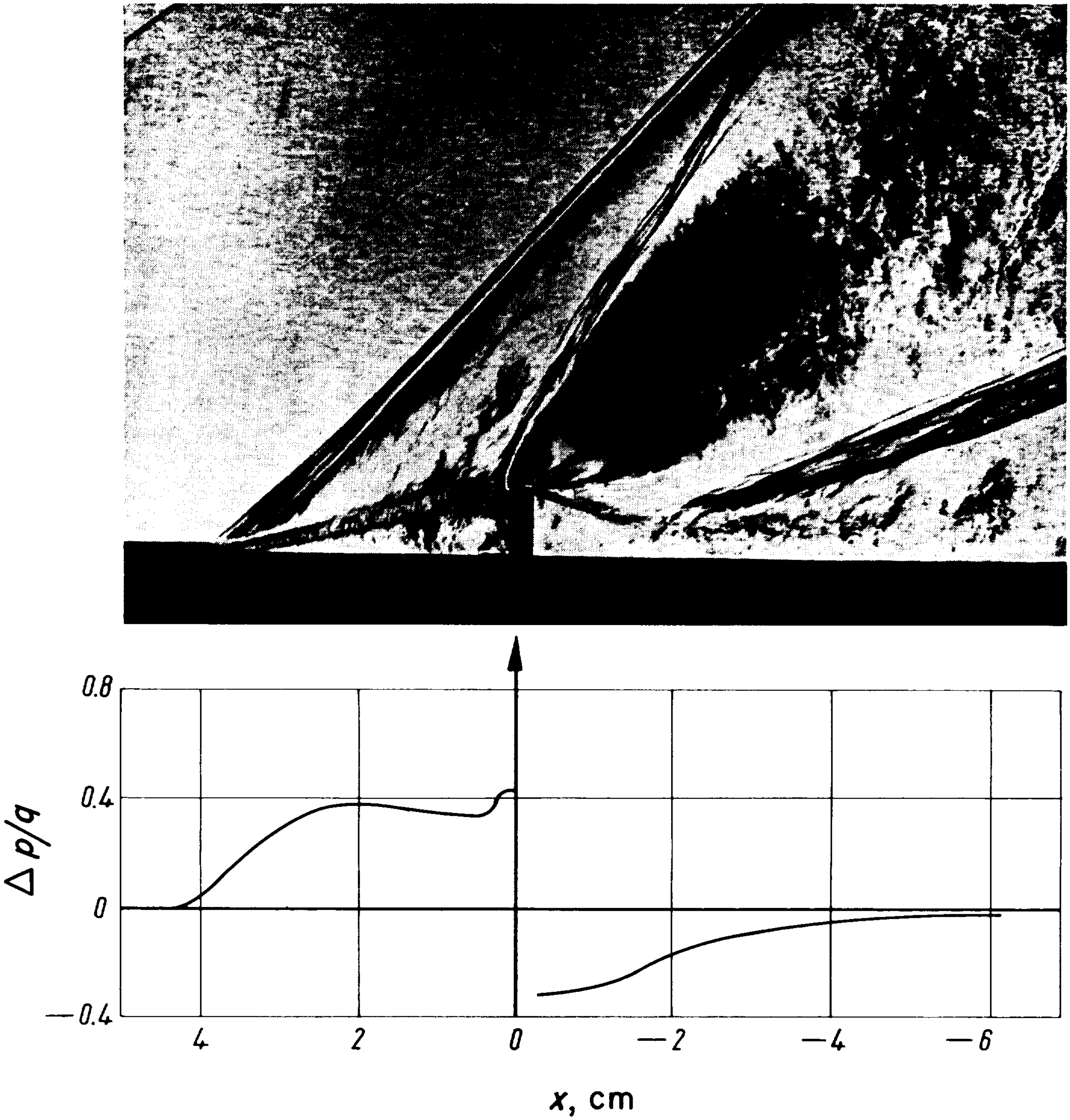


Fig. 4. Flow pattern of solid spoilers in the supersonic range and the relevant pressure distribution; $M = 1.83$, height: 0.8 cm

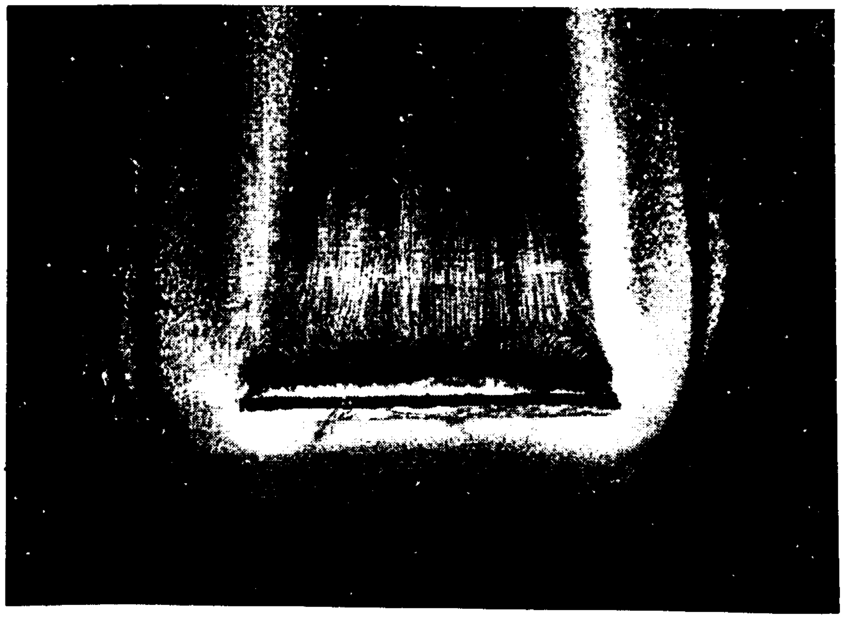


Fig. 5a. Oil film photograph showing the flow pattern of a solid spoiler; $M = 2.21$, height: 0.6 cm. length: 5.9 cm

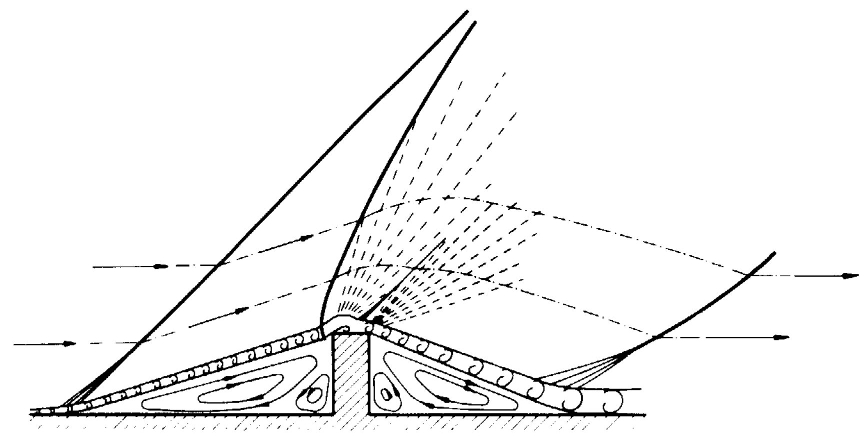
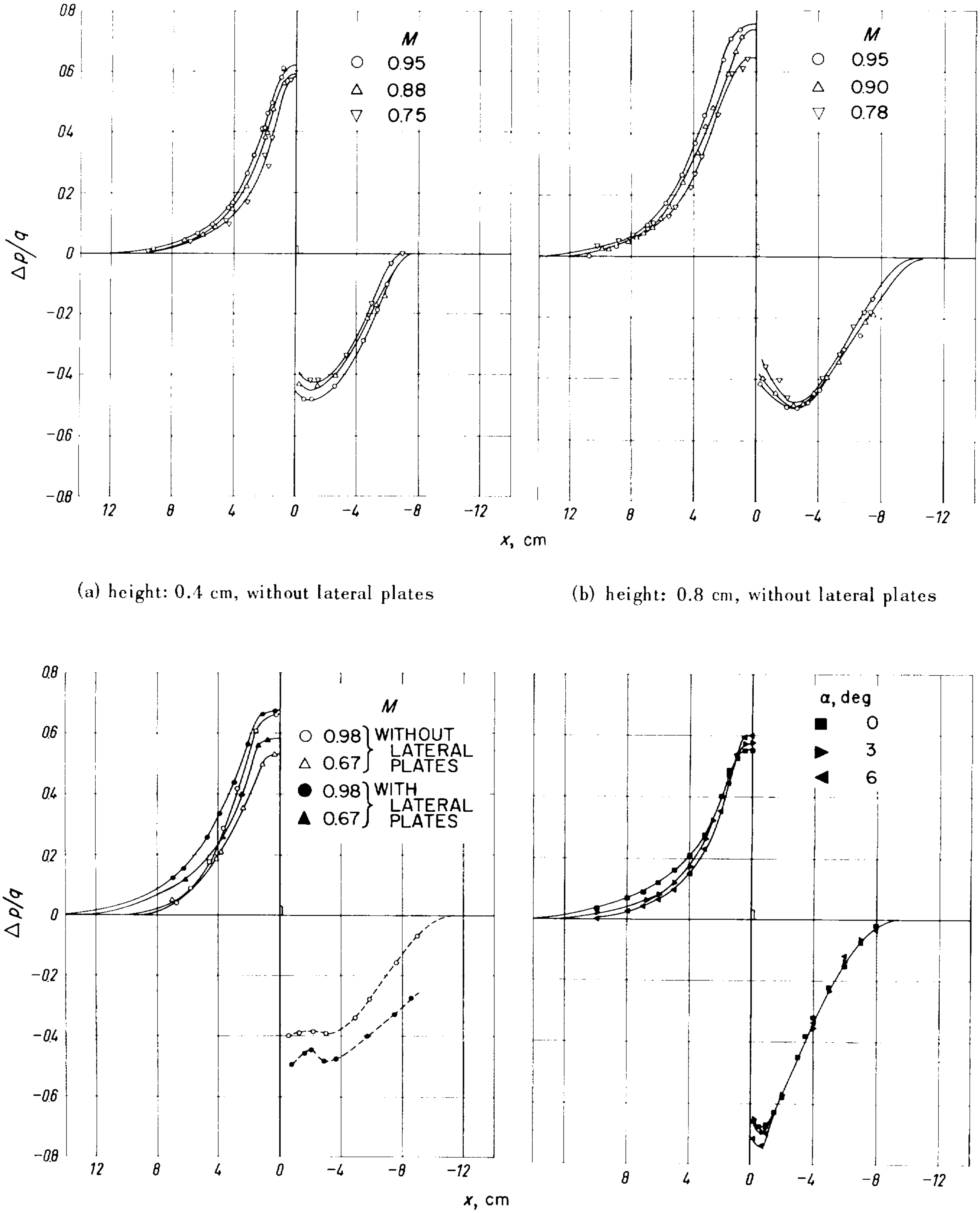


Fig. 5b. Schematic drawing of the flow pattern of a solid spoiler in the supersonic range



(a) height: 0.4 cm, without lateral plates

(b) height: 0.8 cm, without lateral plates

(c) height: 0.6 cm

(d) height: 0.3 cm, with lateral plates $M = 0.9$

Fig. 6. Pressure distributions on solid spoilers in subsonic range

Fig. 7. Flow pattern of a solid spoiler (height: 0.3 cm); $M = 0.98$

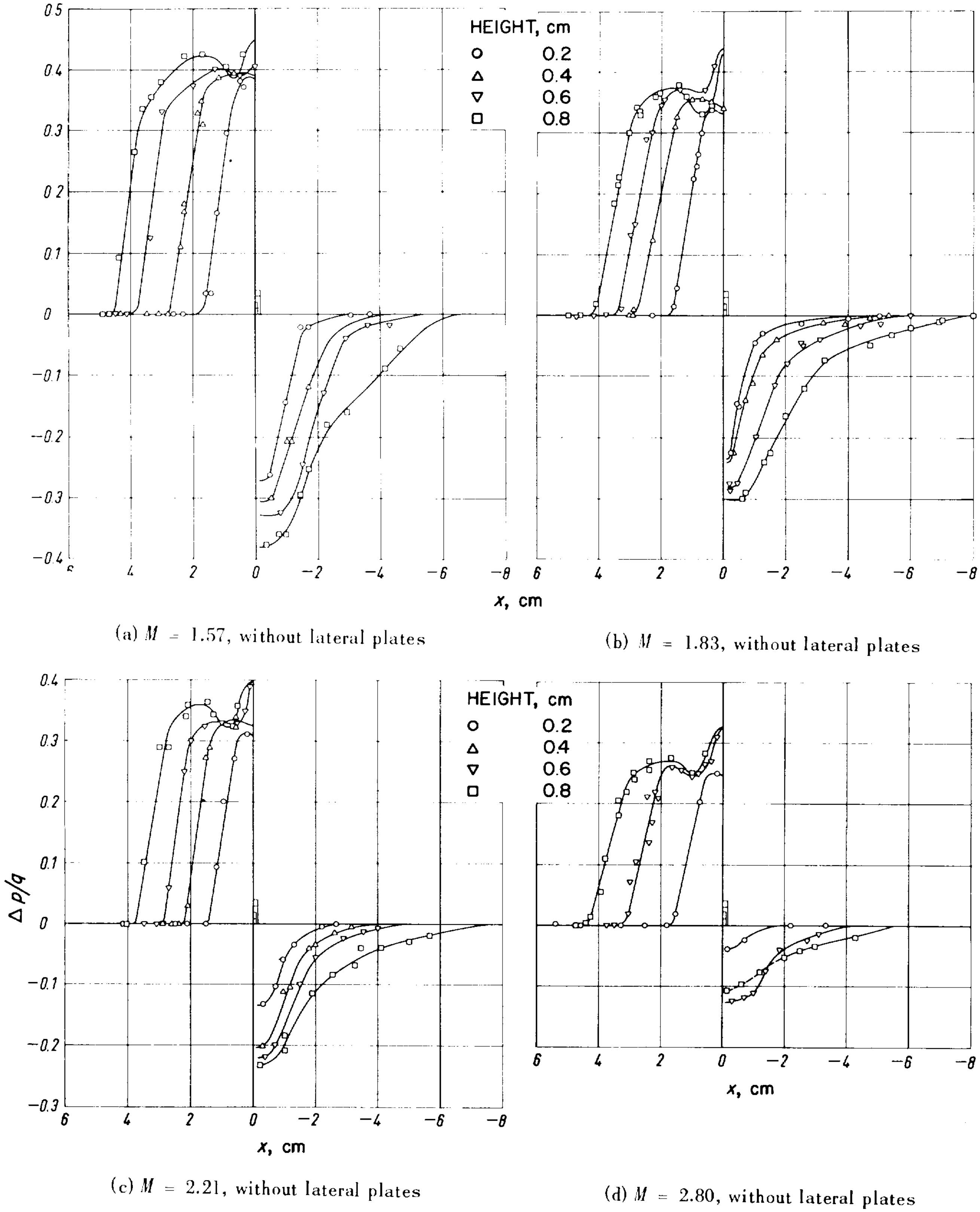


Fig. 8. Pressure distributions on solid spoilers in the supersonic range

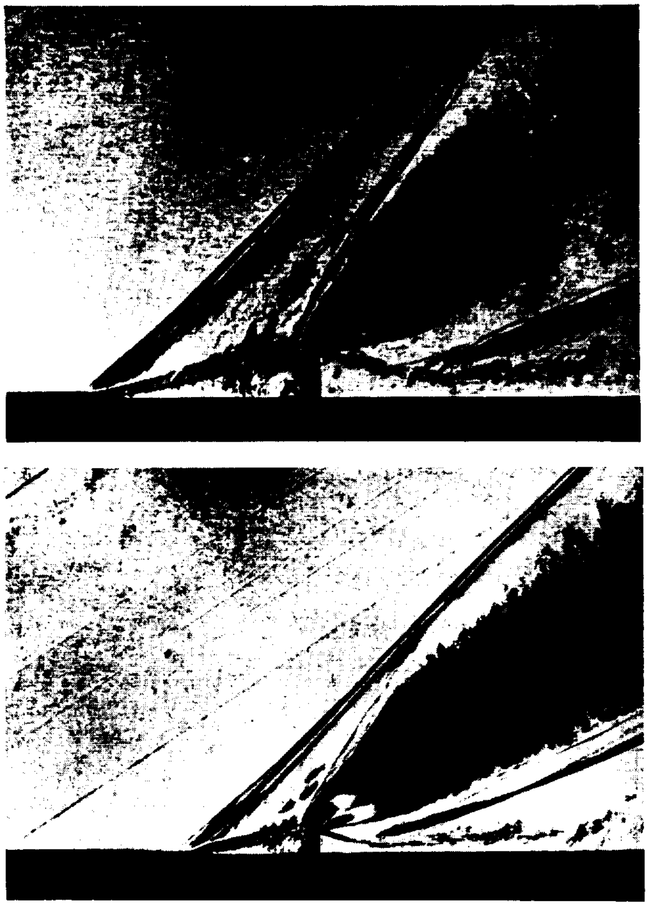


Fig. 9. Flow patterns of a solid spoiler (height: 0.8 cm) at various Mach numbers; (a) $M = 1.57$, (b) $M = 2.21$

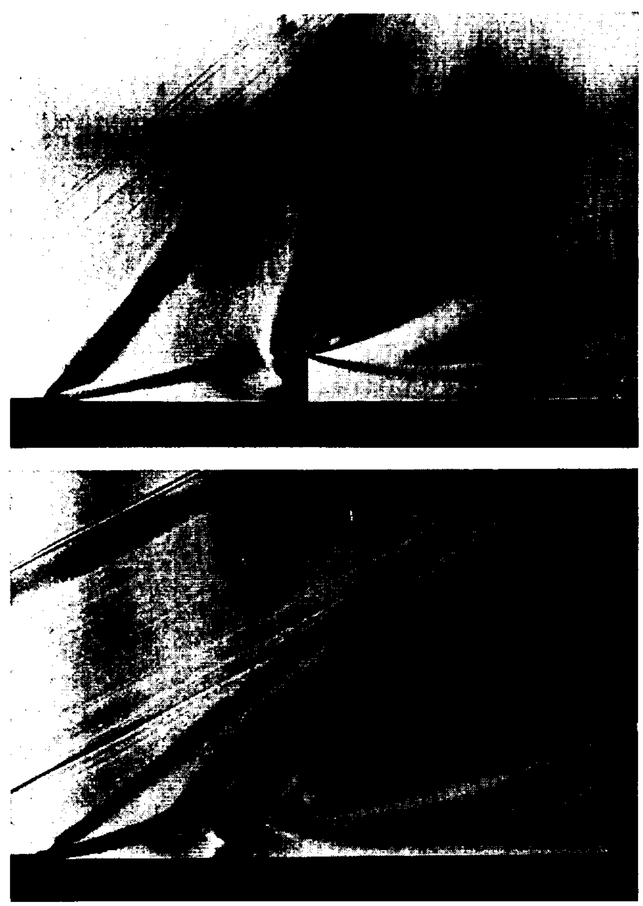


Fig. 10. Flow patterns (spark photographs) of a solid spoiler for various spoiler heights at $M = 1.83$; (a) height: 0.8 cm, (b) height: 0.4 cm

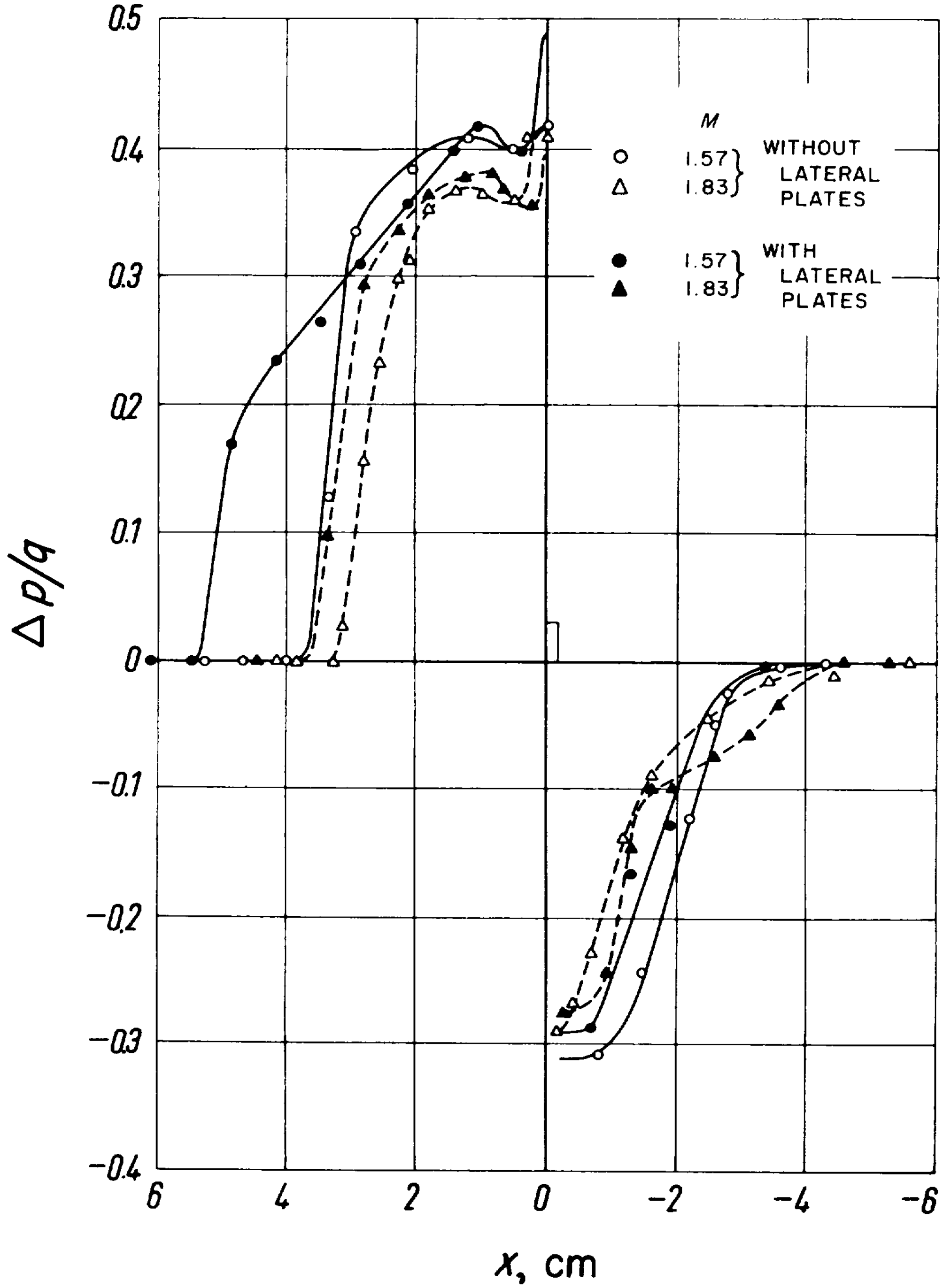


Fig. 11. Pressure distribution of a solid spoiler (height: 0.6 cm) in the supersonic range; influence from the lateral plates

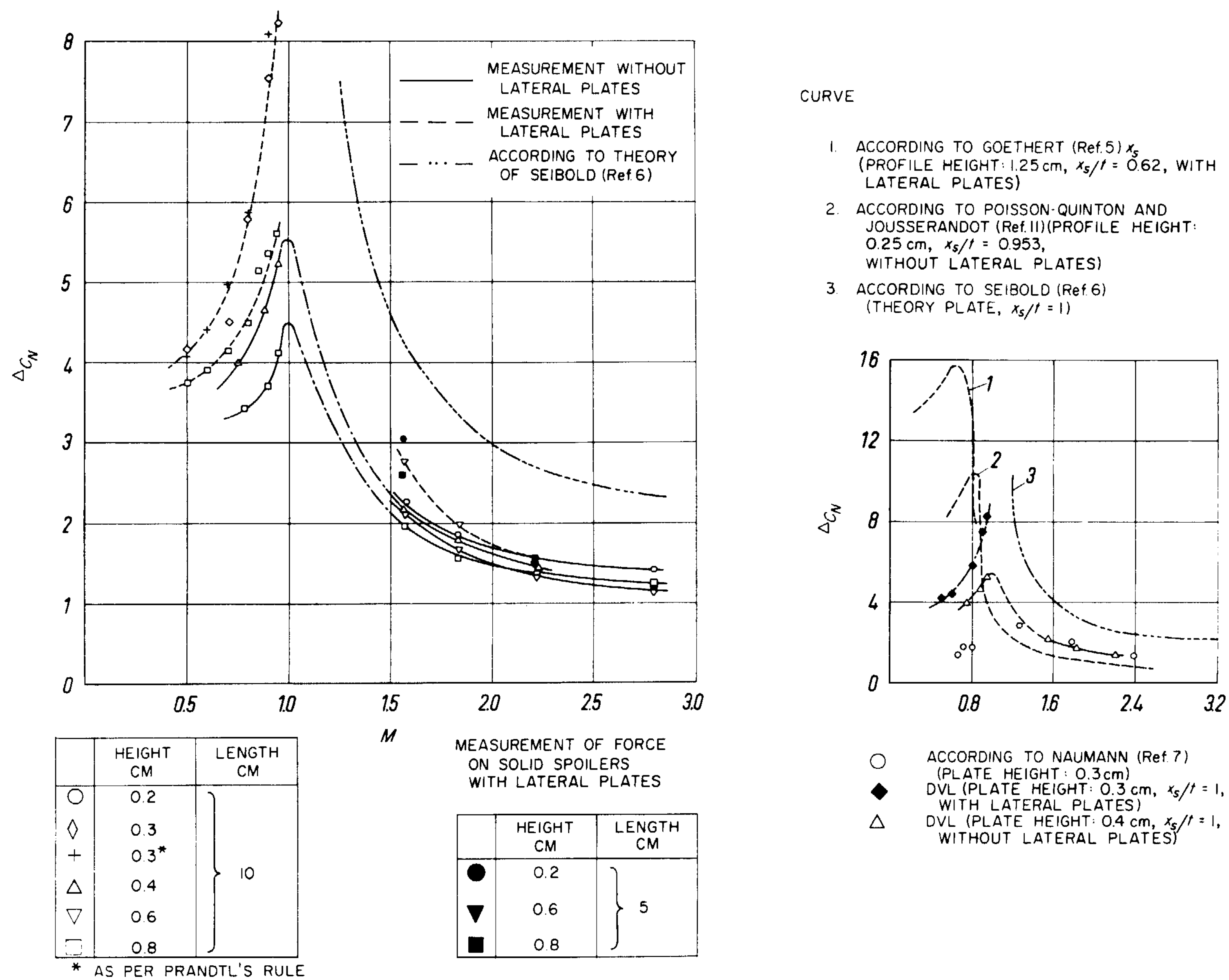
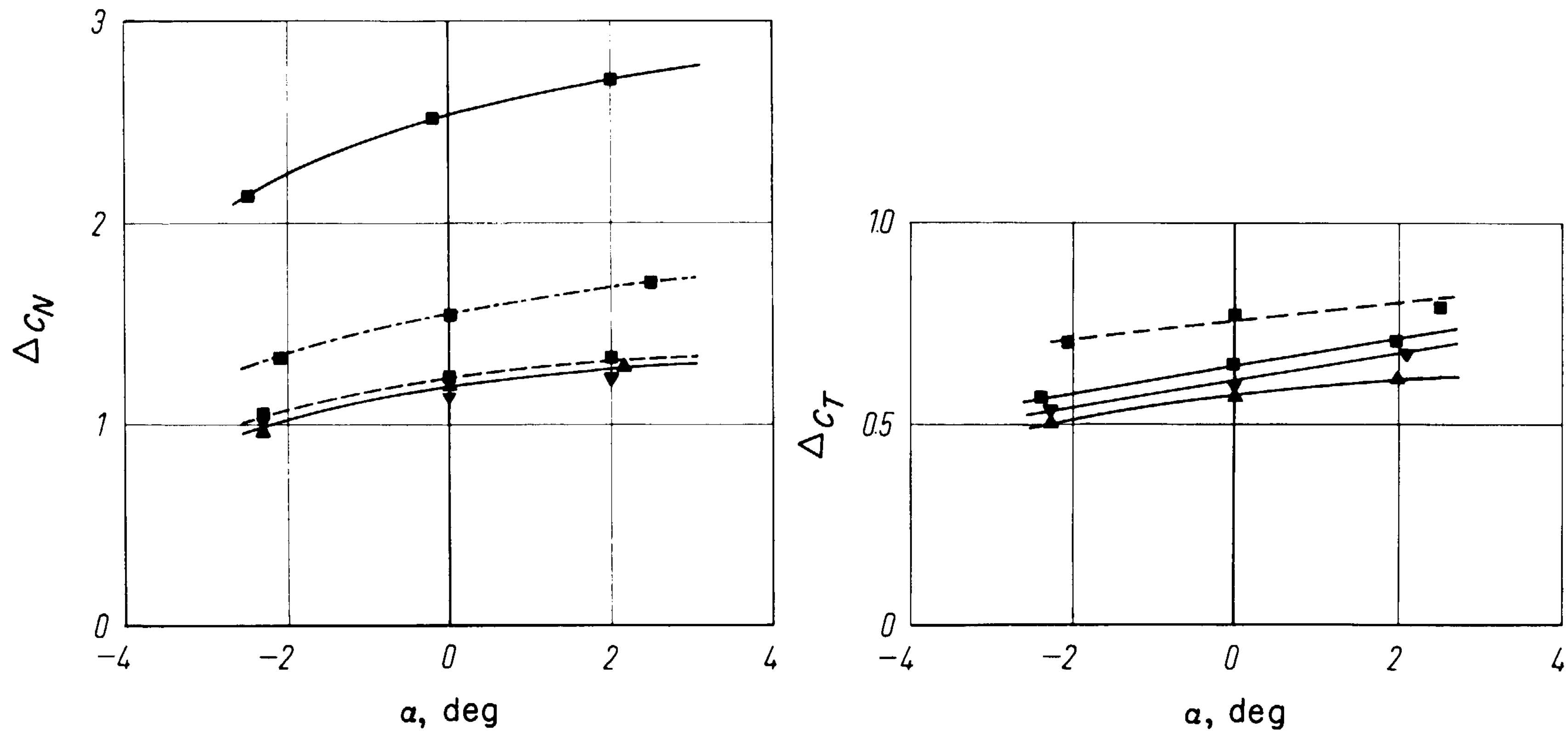


Fig. 12. Survey of measured coefficients of normal force for a solid spoiler, as compared with results known from pertinent literature



	HEIGHT CM	M
▲	0.4	2.80
▼	0.6	2.80
— — ■ — —	0.8	2.80
— · ■ · —	0.8	2.21
——■——	0.8	1.57

(a) Coefficients of normal force

	HEIGHT CM	M
▲	0.4	2.80
▼	0.6	2.80
——■——	0.8	2.80
— — ■ — —	0.8	2.21

(b) Coefficients of tangential force

Fig. 13. Measurements of force by means of a multi-component spoiler balance on end spoilers with lateral plates in the supersonic range

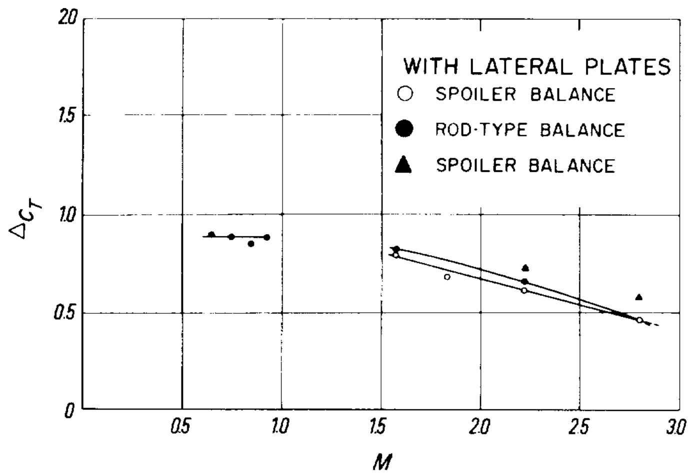
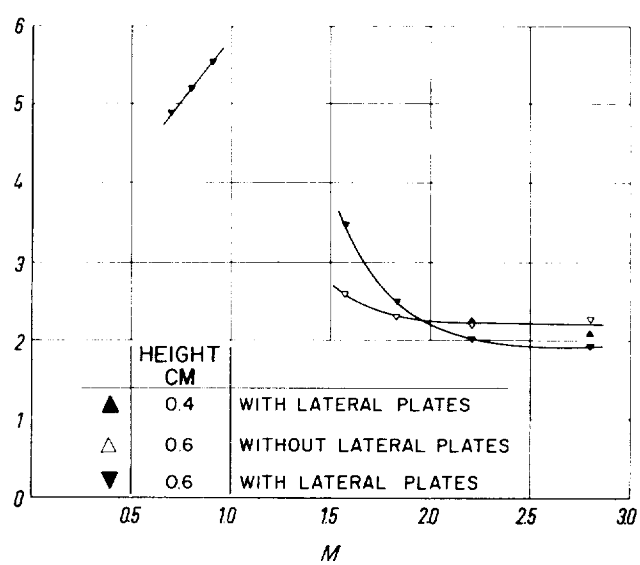


Fig. 14. Coefficients of tangential force for a solid spoiler (height: 0.6 cm)

Fig. 15. Ratio of the normal forces to the tangential forces of a solid spoiler



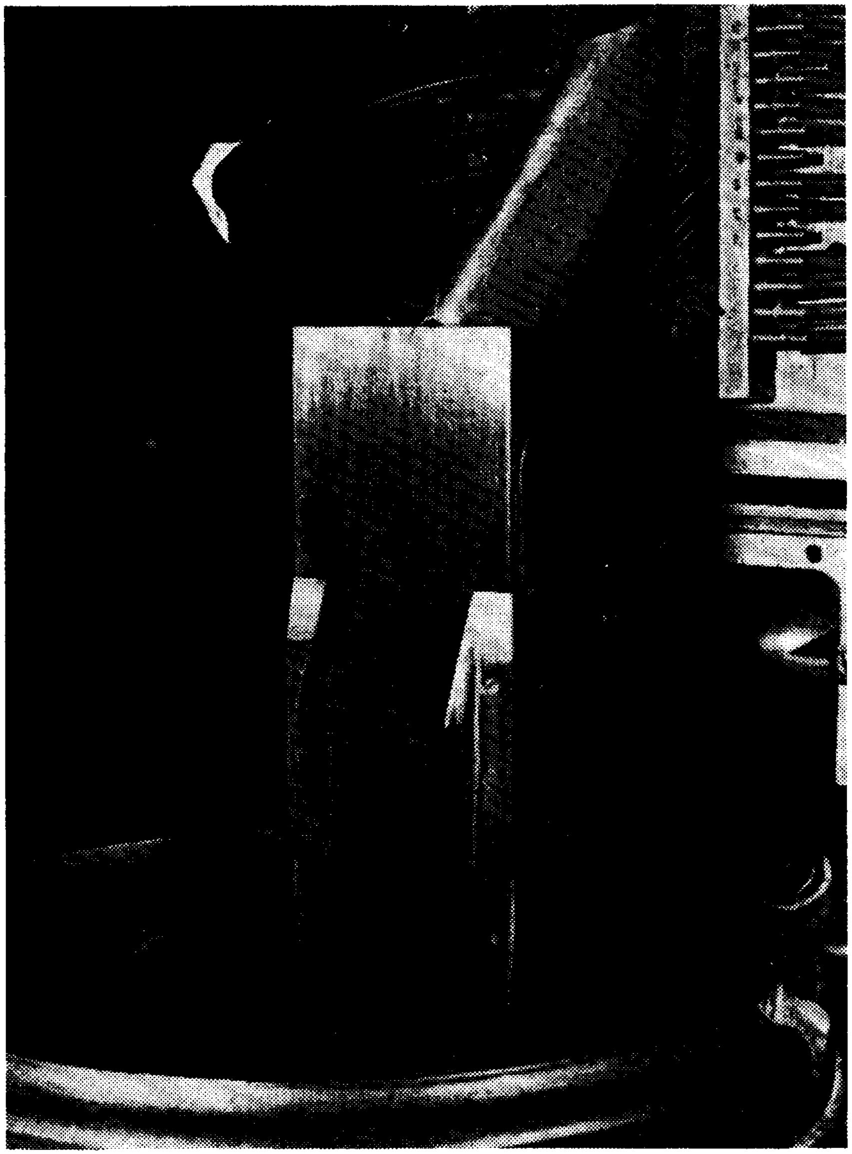


Fig. 16a. Model of a jet spoiler with lateral plates in the test section

A. FLAT PLATE WITH 40 BOREHOLES FOR PRESSURE MEASUREMENTS NEAR THE LONGITUDINAL AXIS OF PLATE

B. SLOTTED NOZZLE FOR JET SPOILER (LENGTH OF SLOT: 4.8 cm, WIDTH OF CONTROL SLOT: 0.1 OR 0.033 cm)

C_1, C_2 LATERAL PLATES (OPTIONAL MOUNTING, C_2 ONLY FOR PHOTOGRAPHS BY MEANS OF OIL AND DARK CHALK)

D. NOZZLE EXIT OF FREE JET

E. HOLDING SWORD OF MODEL

F. AIR INLET

G. DISTRIBUTOR OF CONTROL AIR

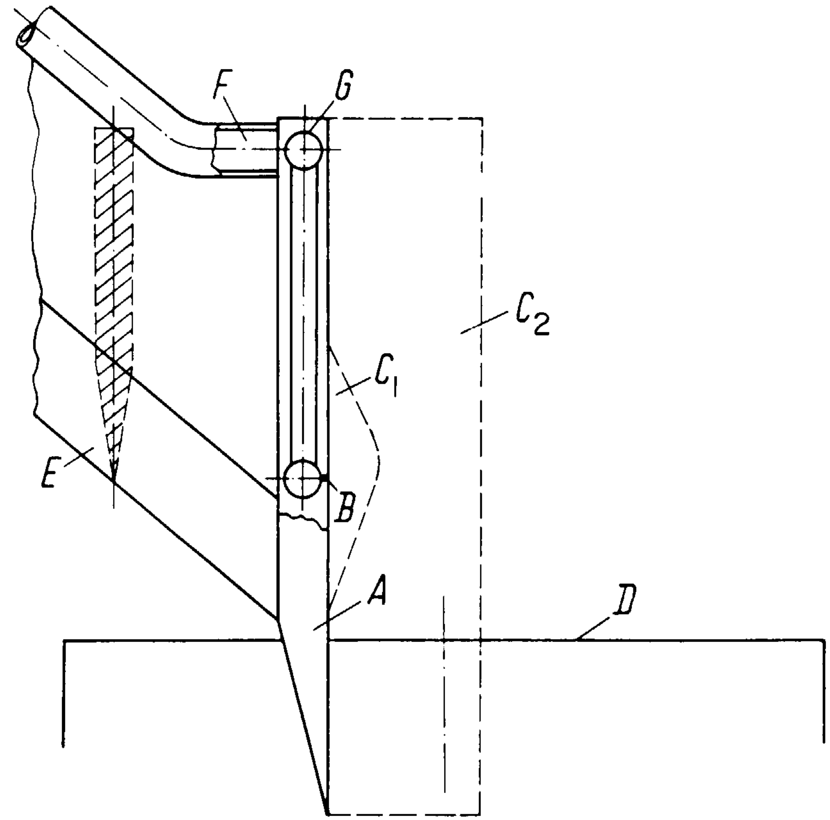
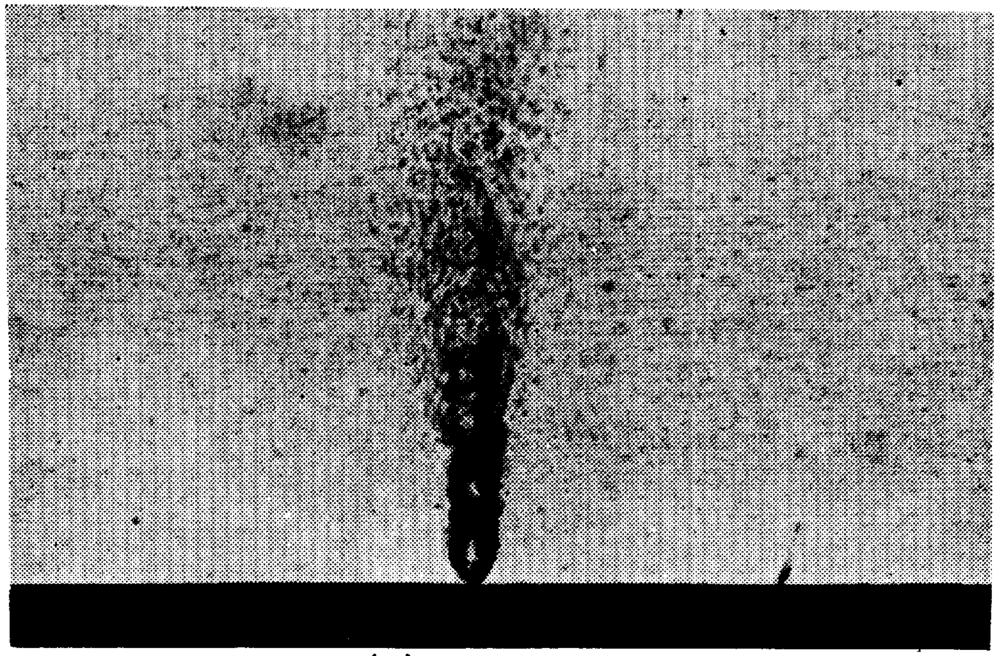
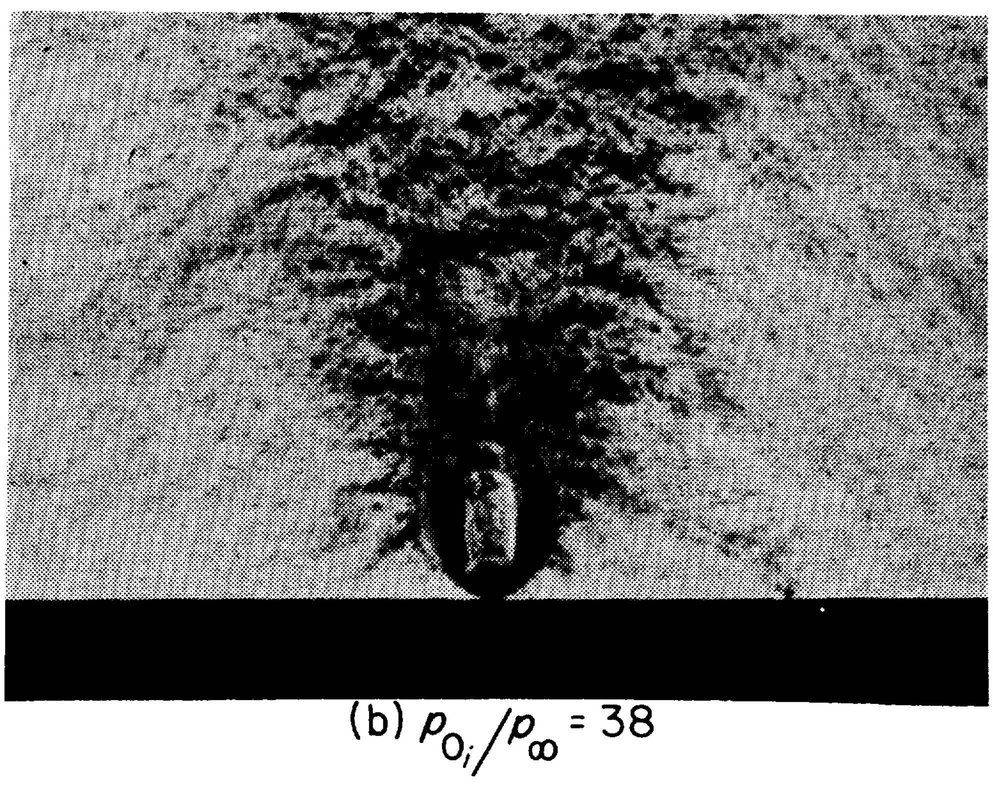


Fig. 16b. Schematic representation of the jet spoiler



(a) $p_{0_i}/p_\infty = 5$



(b) $p_{0_i}/p_\infty = 38$

Fig. 17. Spark photographs of the control jet under different pressure conditions

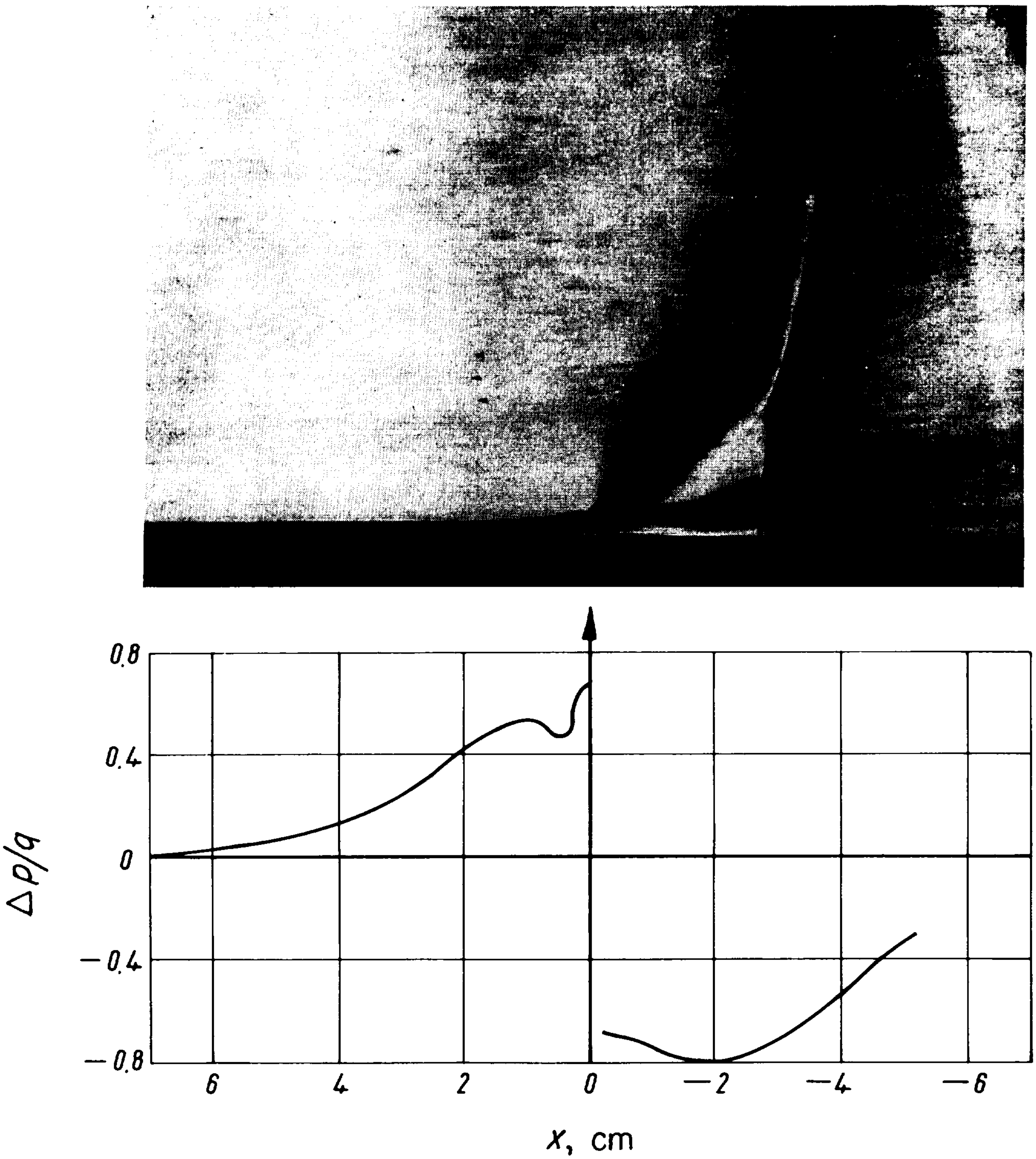


Fig. 18. Flow pattern of a jet spoiler at subsonic speed, and the associated pressure distribution; $M = 0.96$, $p_{0_i}/p_\infty = 7.85$, $s = 0.1$ cm

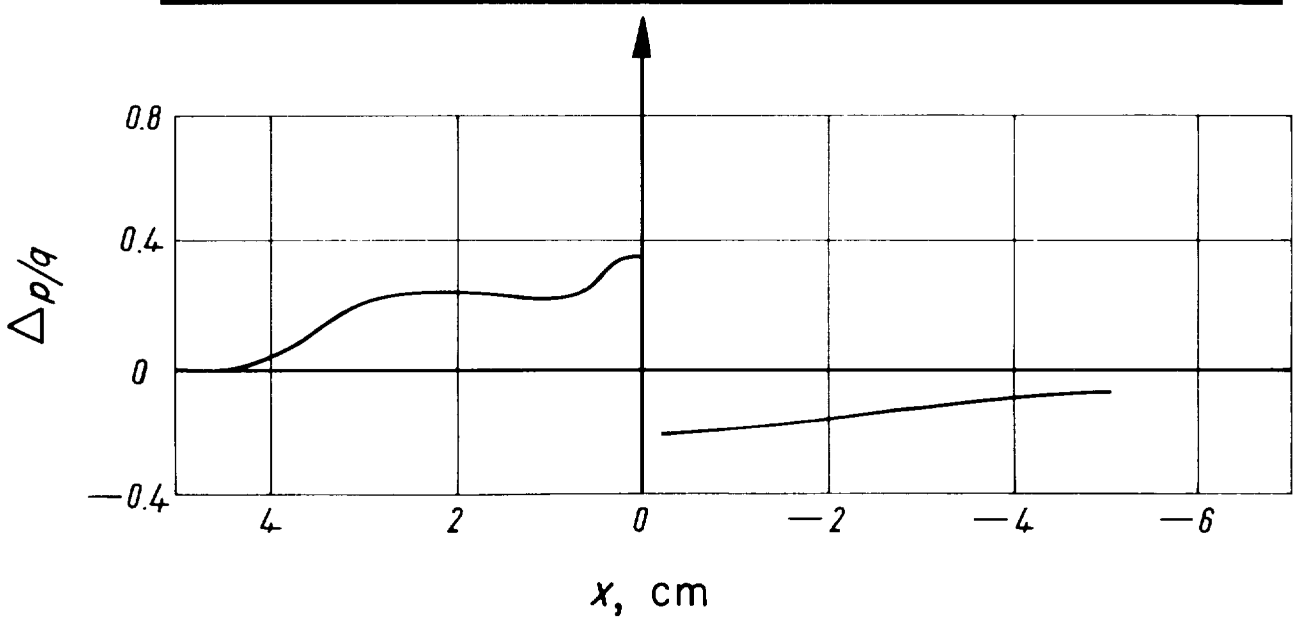
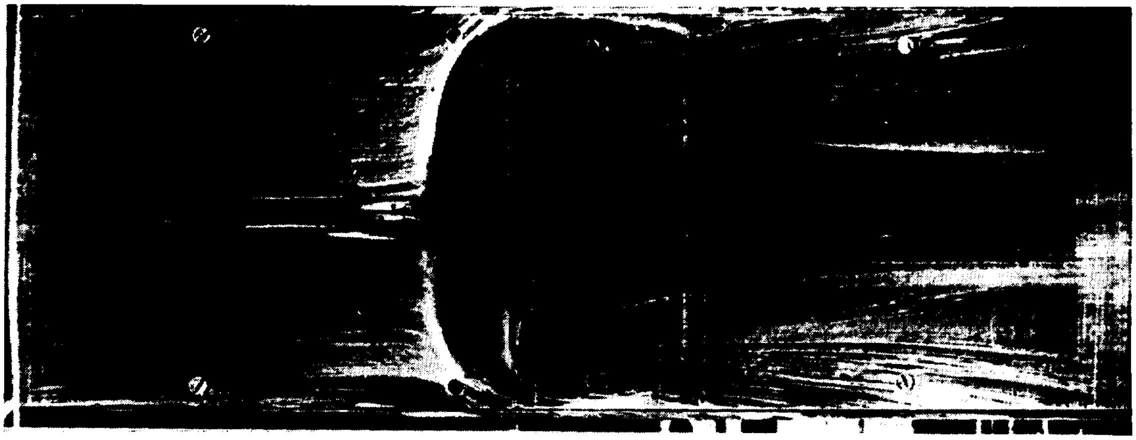


Fig. 19. Flow pattern of a jet spoiler at supersonic speed, and the associated pressure distribution; $M = 1.83$, $p_{0_i}/p_\infty = 20.2$, $s = 0.1$ cm



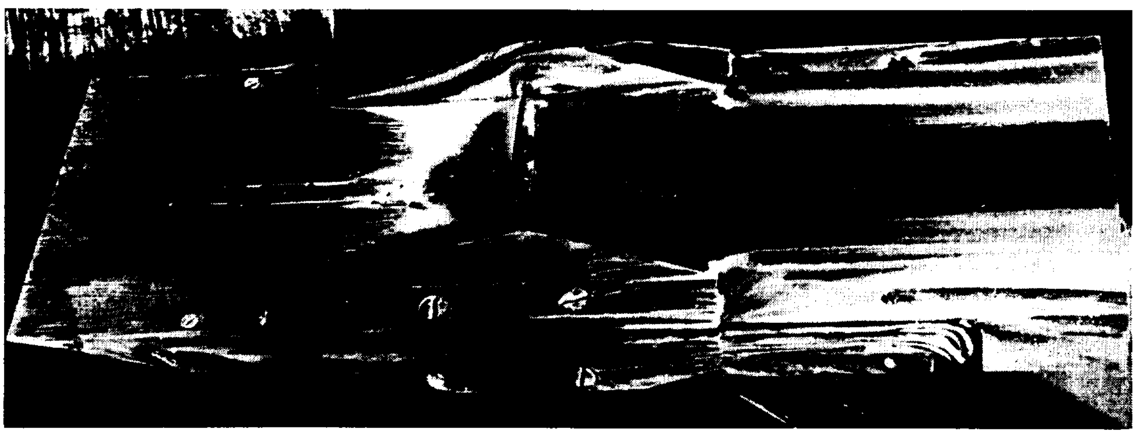


Fig. 20. Oil film photographs, showing the flow pattern of a jet spoiler at supersonic speed ($M = 1.57$); (a) $p_{0_i}/p_\infty = 5.0$, without lateral plates; (b) $p_{0_i}/p_\infty = 5.2$, with lateral plates

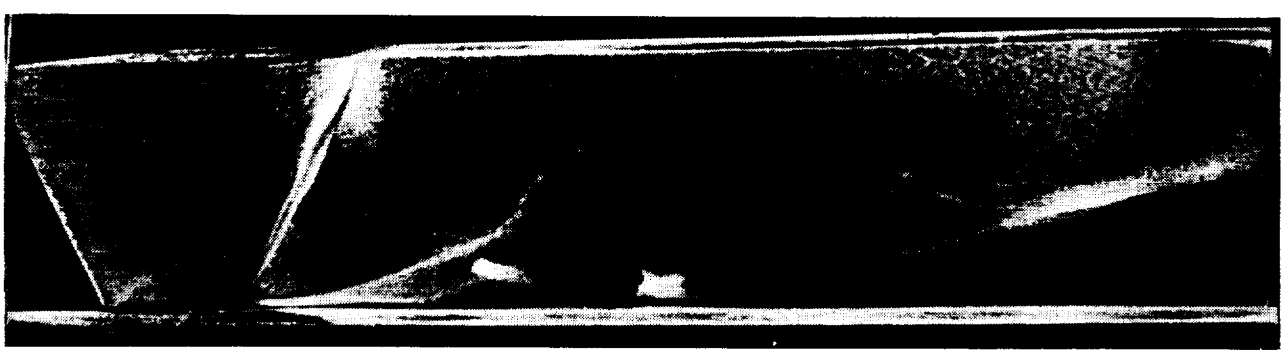


Fig. 21. Oil film photograph (taken on a large lateral plate) of a jet spoiler in flow at supersonic speed ($M = 1.57$, $p_{0_i}/p_\infty = 33.0$)

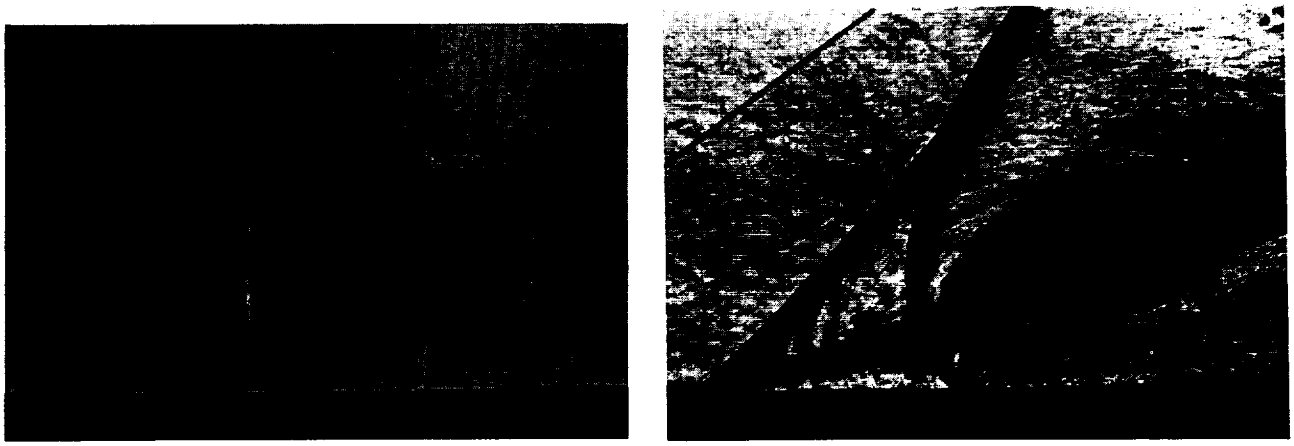


Fig. 22. Schlieren photographs of the flow pattern of a jet spoiler at supersonic speed and about constant pressure ratio $p_{0_i}/p_\infty \approx 26$; (a) $M = 1.57$, (b) $M = 1.83$

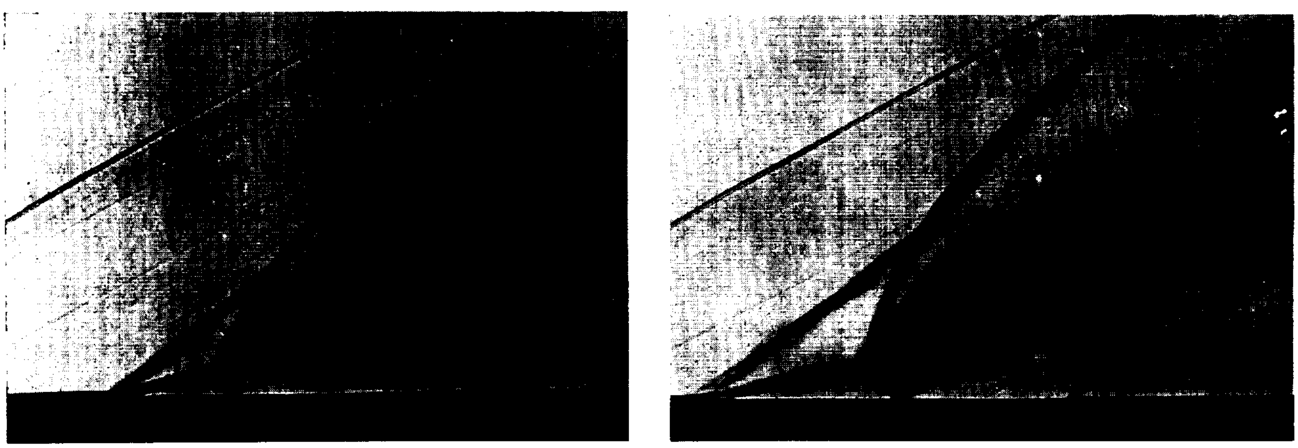


Fig. 23. Schlieren photographs of the flow pattern of a jet spoiler at different pressure ratios and constant Mach number ($M = 2.21$); (a) $p_{0_i}/p_\infty = 14.0$, (b) $p_{0_i}/p_\infty = 33.0$

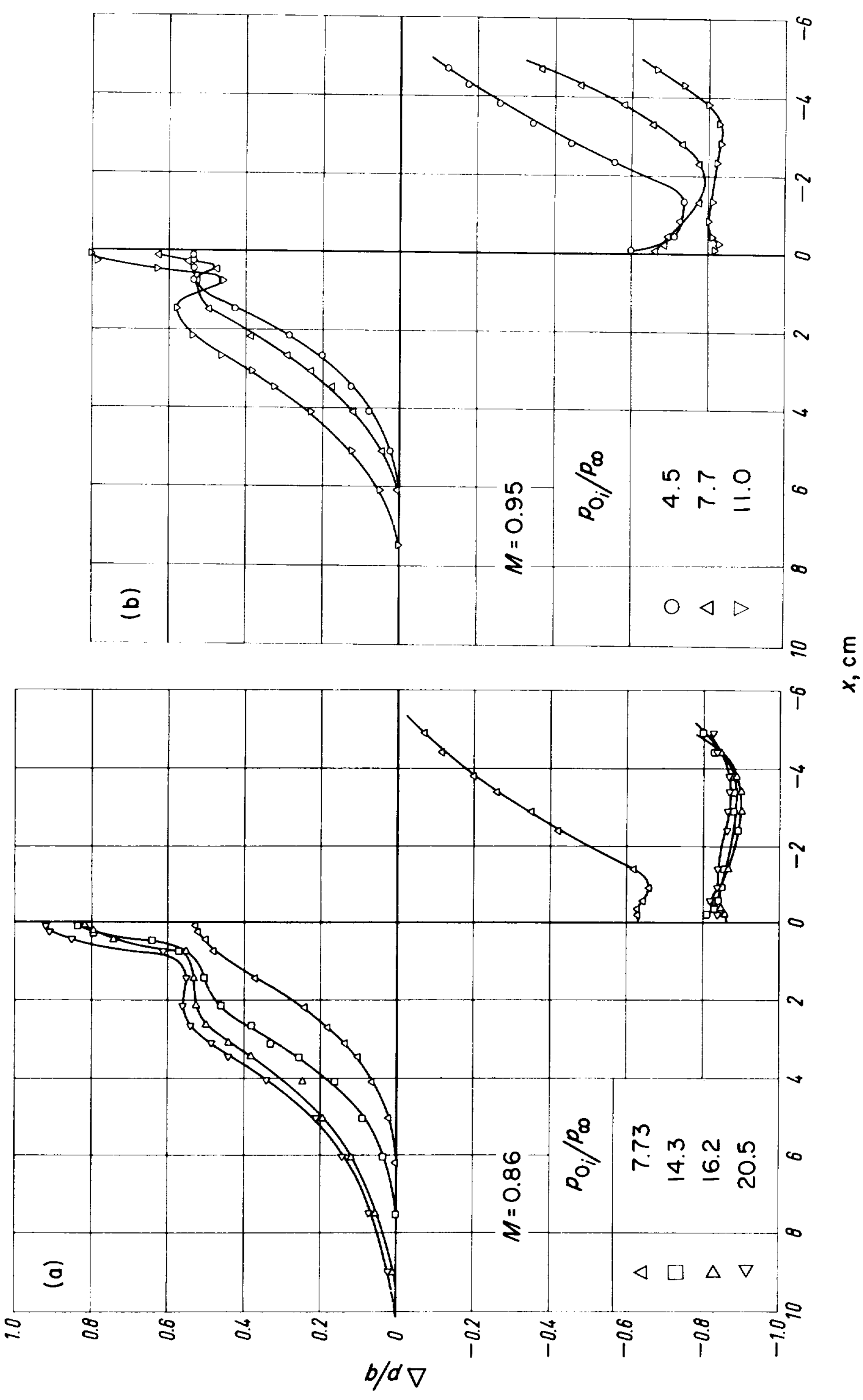


Fig. 24. Pressure distributions of a jet spoiler in the subsonic range, without lateral plates; $s = 0.1$ cm, $b = 4.8$ cm

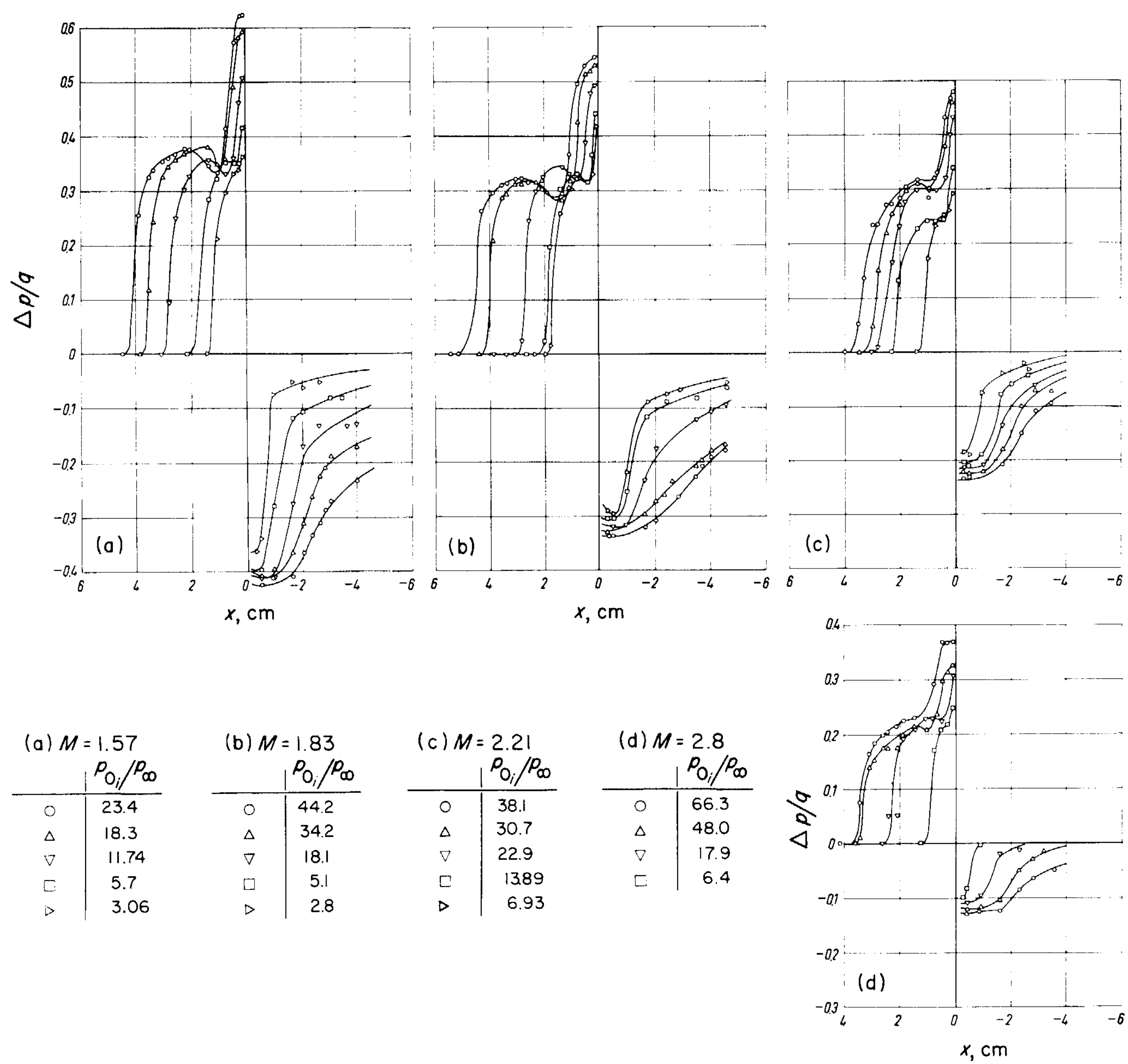
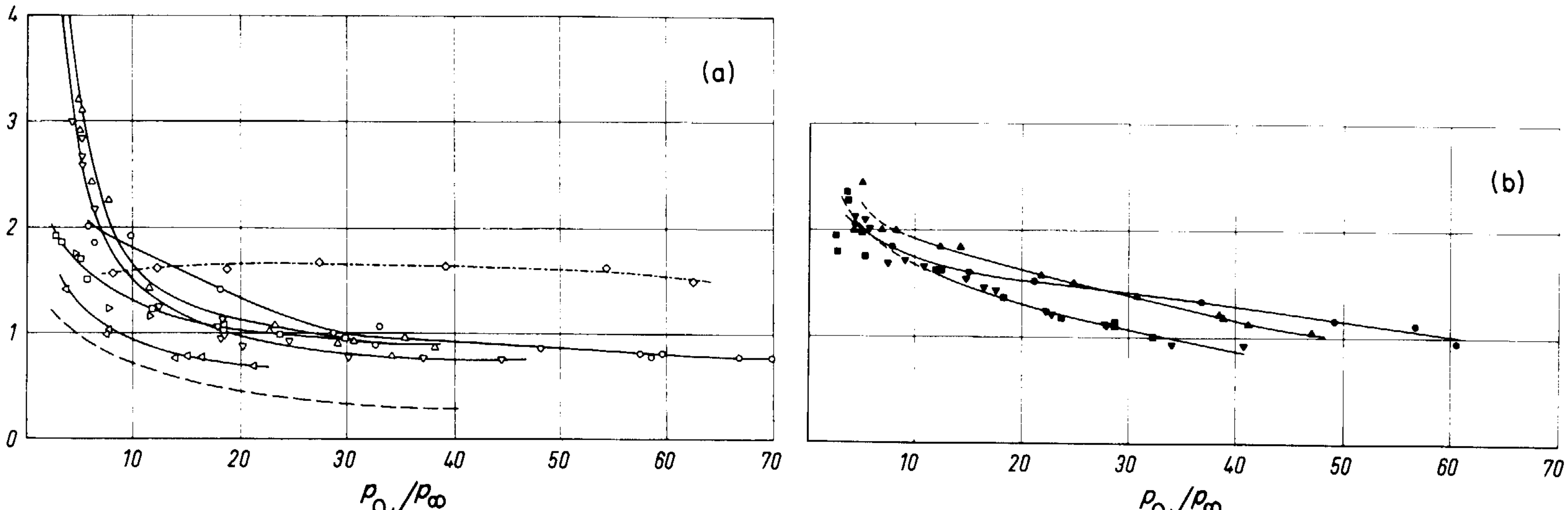


Fig. 25. Pressure distributions of jet spoilers in the supersonic range, without lateral plates



(a) WITHOUT LATERAL PLATES

	M	
○	2.80	DVL
△	2.21	DVL
▽	1.83	DVL
□	1.57	DVL
▷	0.95	DVL
◁	0.86	DVL
+ · ◊ · –	6.0	ROMEO-STERRETT (Ref. 22)*
– – –	2.84	VINSON, AMICK, LIEPMANN (Ref. 20)**

*) $s = 0.127$ cm, $b = 25.4$ cm, SLOT PROFILED
**) CALCULATED

(b) WITH LATERAL PLATES AS PER Fig. 16

	M
●	2.80
▲	2.21
▼	1.83
■	1.57

Fig. 26. Effect of normal force by interference of control jet and main stream in relation to effect of normal force in the case of expansion of control jet under vacuum conditions; $s = 0.1$ cm, $b = 4.8$ cm

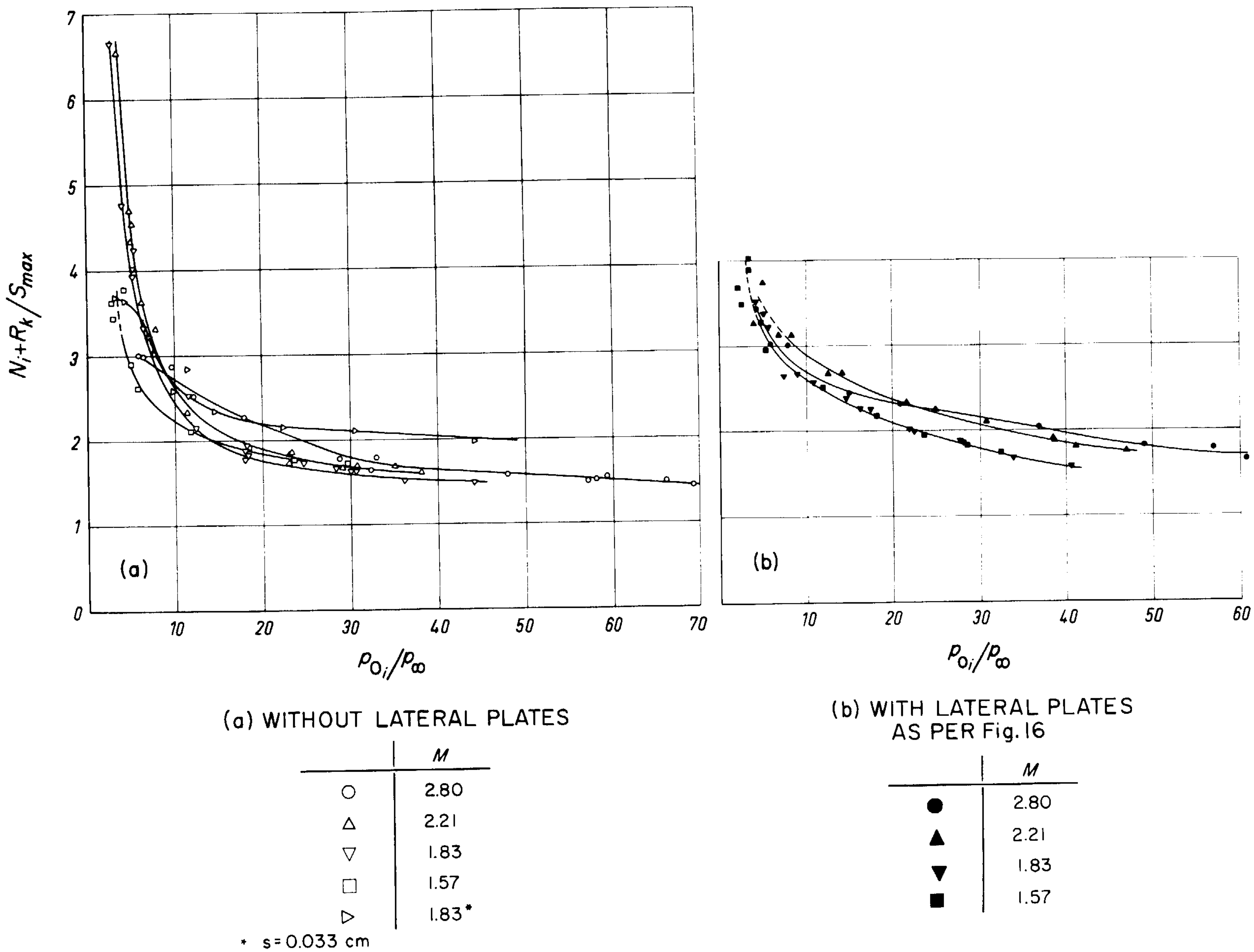


Fig. 27. Total of control forces normal to baseplate in relation to maximum thrust of control jet with expansion on equal pressure exhaustion at p_∞; $s = 0.1$ cm, $b = 4.8$ cm

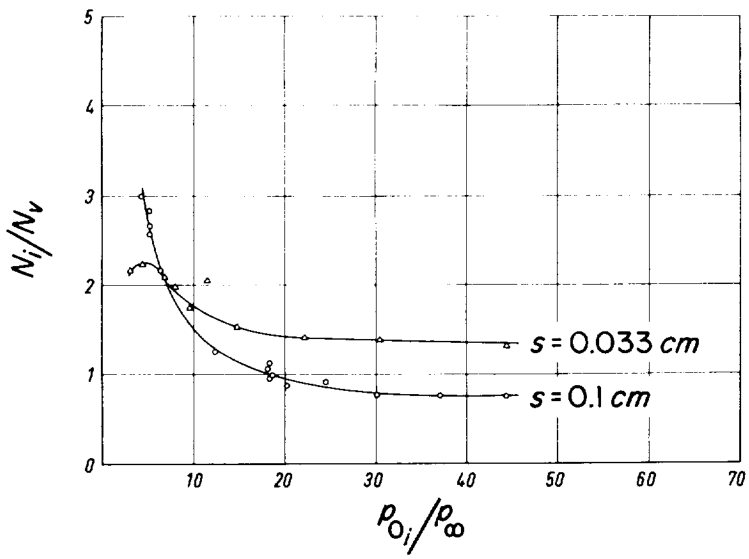


Fig. 28. Comparison of the effect of normal force with different width of control slot, $M = 1.83$, $b = 4.8$ cm, without lateral plates

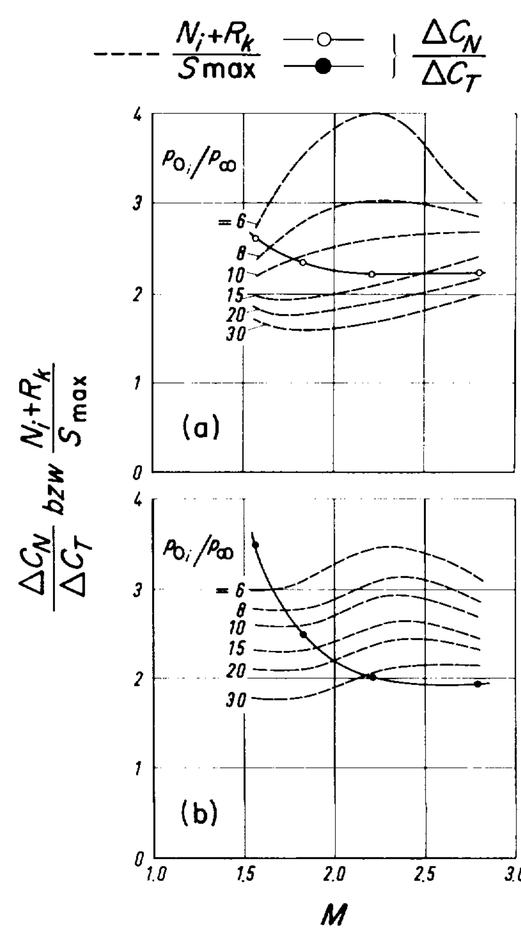


Fig. 29. Comparison of the solid spoiler with a jet spoiler regarding the control effect normal to baseplate in relation to the tangential force (of solid spoiler) or to loss of $s = 0.1$ cm, $b = 4.8$ cm

(a) without lateral plates

(b) with lateral plates

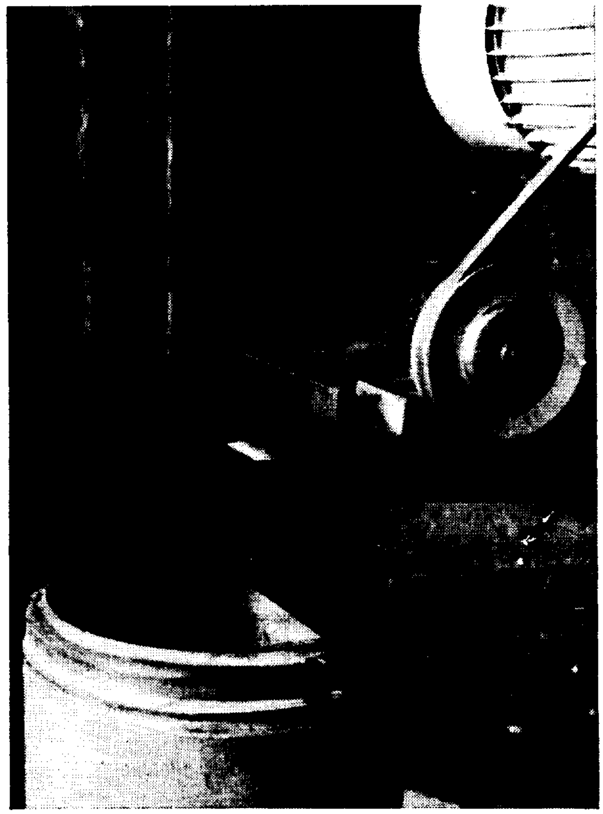


Fig. 30. Test arrangement for the examination of the process of composition and decomposition of the flow pattern on an extending or retracting spoiler

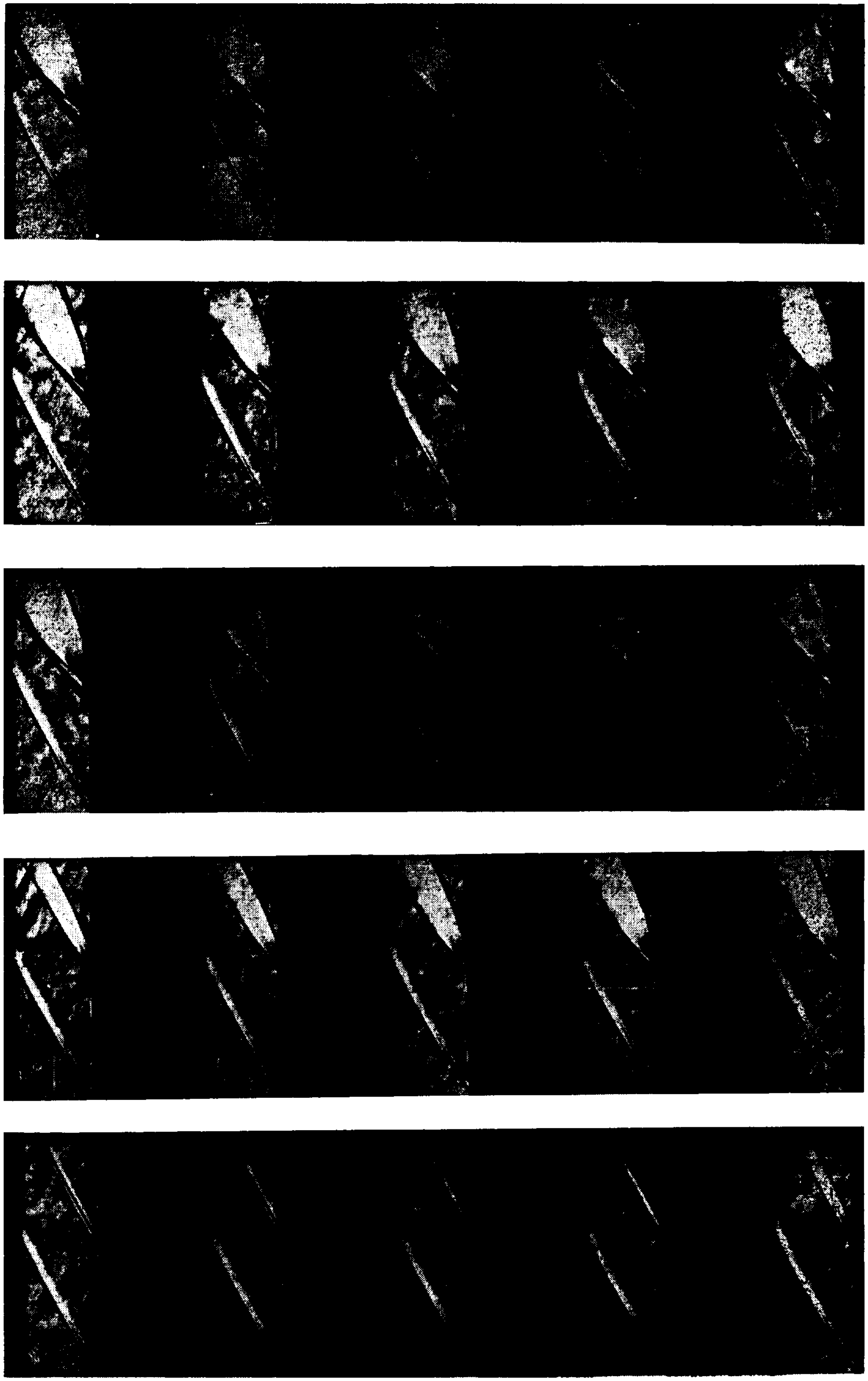


Fig. 31. High-frequency photographs of an extending spoiler (image frequency 5000/sec); $M = 2.21$, $h_{max} = 0.7$ cm

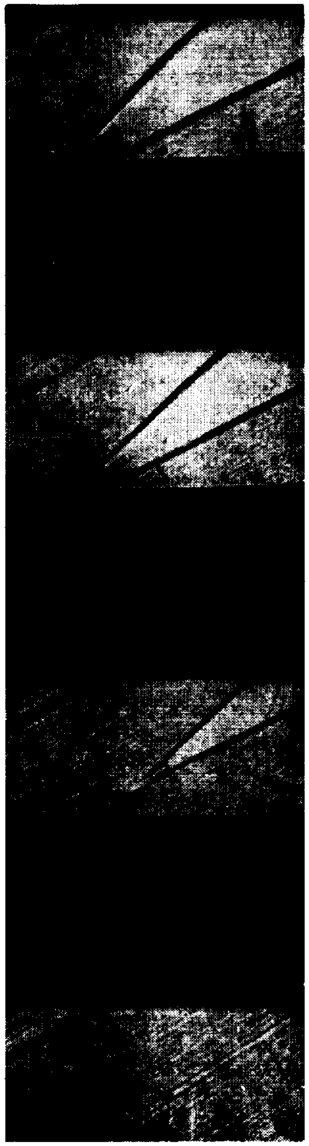


Fig. 32. High-frequency photographs of a retracting spoiler; $M = 1.83$